Optical Network Design and Modelling

Edited by
Harmen R. van As and Admela Jukan

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CONTENTS

PREFACE

Significant technological progress, an increasing variety of communication services, growing demand for network flexibility and availability as well as a fast expanding traffic volume continuously drive telecommunication networks into new, fast evolving generations. With optical networks, a new, highly promising age of communication appears on the horizon. Affordable broadband communications for everybody might soon become reality.
Photonic or optical networks exhibit novel properties like optical transparency over global distances, nearly unlimited transmission capacity, transmissions with extremely low bit-error rates and a hitherto unmatched flexibility in operation. A powerful, universal communication structure is developing. Existing networks and the wealth of different communication services can be integrated naturally. In addition, the same optical infrastructure can for instance also be exploited for the terrestrial part of mobile communications, for highway and air-traffic control systems as well as for analog and digital TV-distribution networks.

We are now starting to face an era of world-wide use of advanced optical technologies being applied in optical networks. In this promising new environment, optical network design and modelling is an essential issue for planning and operating networks of the next century. Many research programs make enormous efforts substantiating new approaches for optical networking. The main issues are being widely investigated, not only for WDM networks based on wavelength division multiplexing but also for networks based on optical time division multiplexing (OTDM) and optical packet switching.

This book contains part of the contributions presented at the working-conference *'Optical Network Design and Modelling'* held in Vienna, February 24-25, 1997. This conference has been the first meeting of an annual event of Working Group WG10 *'Photonic Communication Networks'* of the Technical Committee TC6 of the International Federation for Information Processing IFIP. This working group is aimed at strengthening research and development of photonic networks; to explore their potentials; to accelerate early development of these networks; and to provide a platform for presenting and discussing research activities, major achievements, and trends involving these all-optical communication networks.

In order to stimulate progress in optical networking, the major scope of the working group is to foster exploration of architectures, system designs,

control mechanisms, and applications that exploit the abundant transmission capacity and flexibility of photonics; and to promote development of analytical and simulation tools as well as methods for analysing, operating, dimensioning, and planning such networks.

The contributions in this book reflect these activities to promote the widespread introduction of photonic communication networks that hold the promise of solving several problems in the current generation of networks, among them restricted transmission capacity and limited performance capability.

The papers have been ordered into the following sections:

- OAM functions and layered design of photonic networks
- Network planning and design
- Network modelling
- Network availability and performance modelling

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PART ONE

OAM functions and layered design of photonic networks

WDM Supervision in PHOTON as a Basis for OAM of All-Optical Transport Networks

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Abstract

A key issue for the Operation & Maintenance (OAM) of an all-optical transport network is failure localisation in the network. The WDM supervision concept in the ACTS project PHOTON (Photonic Transport Overlay Network) achieves this by the introduction of defects and maintenance signals similar to existing transport networks. In the following this concept is explained.

This work was supported in part by the European Commission. The contents of this paper is solely the responsibility of the authors.

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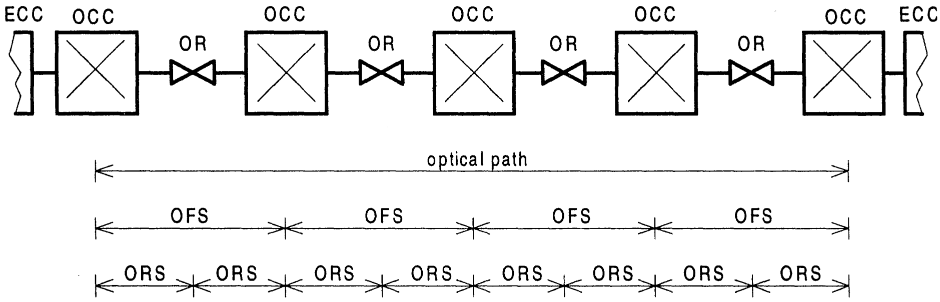
The used Layer Concept

For the purpose of defining OAM principles a layered model for the optical transport network is very useful. Within PHOTON, which utilises Wavelength Division Multiplexing (WDM), such a model has been defined, based on the generic architecture of the ITU G.805 recommendation, by introducing three new layers between the existing physical media layer and the existing transport layer networks (e.g. SDH or ATM). The new proposal of G.otn for optical transport networks has not been taken into account, since it was not available at the time the PHOTON model had been established and G.otn currently is not more than a draft. Nevertheless the standardisation process within G.otn will be observed carefully. The G.lon, now already agreed as G.681, on the other hand, deals only with WDM point-to-point connections supporting SDH and cannot be applied directly to all-optical transport networks.

The three layers for the optical transport network are:

- Client regenerator section layer
- **Optical path layer**
- **Optical frequency section layer**
- **Optical regenerator section layer**
- Physical media layer

Figure 1 shows the corresponding sections in the network. The optical path can be seen as a transport pipe through the optical transport network. The optical frequency section extends between the optical cross connects (OCCs), and the optical regenerator section is terminated by optical regenerators (ORs) or optical nodes.



OFS	Optical frequency section	OCC	Optical cross connect
OR	Optical regenerator	ECC	Electrical cross connect

Figure 1: Optical path and optical sections in optical transport networks

Each of the three optical layers has (at least logically) an overhead assigned which carries WDM supervision information. These layer overheads have the same purpose as the overheads in the SDH transport networks and represent the payload independent information in the optical transport network. This information is used for network internal purposes only. In the PHOTON optical transport network it is proposed to use special WDM channels (so called overhead channels) reserved only for the purpose of overhead transmission and network management information transport within the optical transport network. Maintenance signals are part of the layer overheads and transported within the overhead channels to enable failure detection, failure localisation and failure suppression inside the optical transport network. The generation of these signals is strongly related to the defects detected by the optical nodes in the optical transport network.

Defects and Maintenance Signals

Figure 2 lists the defects and maintenance signals for each of the three optical layers. Here it is assumed that all three overheads are transported in one overhead channel.

	Optical regenerator section layer	Optical frequency section layer	Optical path layer
Maintenance signals	ORS-alarm indication signal	OFS-remote defect indication	OP-alarm indication signal
	OH failure indication signal	Channel defect indication	OP-remote defect indication
	-	Frequency shift indication	-
	-	Unequipped signal	-
Detected defects	Loss of signal	Loss of channel	Path identifier mismatch
	Loss of payload	Channel degrade	Loss of tributary channel signal
	Loss of overhead	Shift of frequency	Degradation of tributary channel signal

Figure 2: Defects and maintenance signals

In the following each defect and maintenance signal is described shortly:

Defects

- **Loss of signal (LOS):** the complete WDM signal fails.
- **Loss of payload (LOP):** all payload channels fail at the same time and the overhead is still present.
- **Loss of overhead (LOH):** the overhead fails.
- **Loss of channel (LOC):** a single payload channel fails.
- **Channel degrade (CD):**the signal quality of a single channel is below a certain level.
- **Shift of frequency (SOF):** the frequency of a single channel is out of range.
- **Path identifier mismatch (PID):** an optical path signal is not the one expected at the path end.
- **Loss of tributary channel (LTC):** an optical single channel signal, which is provided to the optical transport network by the client network, fails.
- **Degradation of tributary channel (DTC):** the signal quality of an optical single channel signal which is provided to the optical transport network by the client network is below a certain range.

Maintenance signals

- **ORS - alarm indication signal (ORS-AIS):** informs all downstream network elements along an OFS about LOS or LOP.
- **OFS - remote defect indication (OFS-RDI):** informs the next upstream optical node about LOS or LOP.
- **Channel defect indication (CDI):** informs the next upstream optical node about LOC or CD.
- **Frequency shift indication (FSI):** informs the next upstream optical node about SOF.

- **Overhead failure indication signal (OHFIS):** informs all downstream network elements along and OFS about faulty overhead.
- **Unequipped signal (UNEQ):** informs the downstream optical nodes about the intentional unequipped state of a payload channel.
- **OP - alarm indication signal (OP-AIS):** informs the downstream optical nodes about a faulty payload channel.
- **OP - remote defect indication (OP-RDI)** informs the upstream optical nodes about a faulty payload channel

Maintenance Signal Interaction

In this section the maintenance signals and their interaction are presented with the simple example depicted in figure 3. A fibre break between an optical cross connect and an optical regenerator is assumed. This network failure results in the detection of the LOS defect in the optical regenerator directly behind this break. As a result ORS-AIS is generated in downstream direction. This signal informs the OCC about the failure and suppresses its defect detection for this fibre. Additional the OHFIS is generated by the OR, informing the OCC about the loss of the overhead and the location of the reporting OR. The OCC reacts with generation of additional maintenance signals. An OFS-RDI signal informs the upstream OCC about the failure of the OFS and enables e.g. to stop billing for this line. In downstream direction the OCC generates an OP-AIS for all optical path affected by this fibre break. This signal suppresses the defect detection for these paths (e.g. LOC) in the downstream OCCs. An OP-RDI is generated at the end of the optical path to inform the other path end about the defective connection.

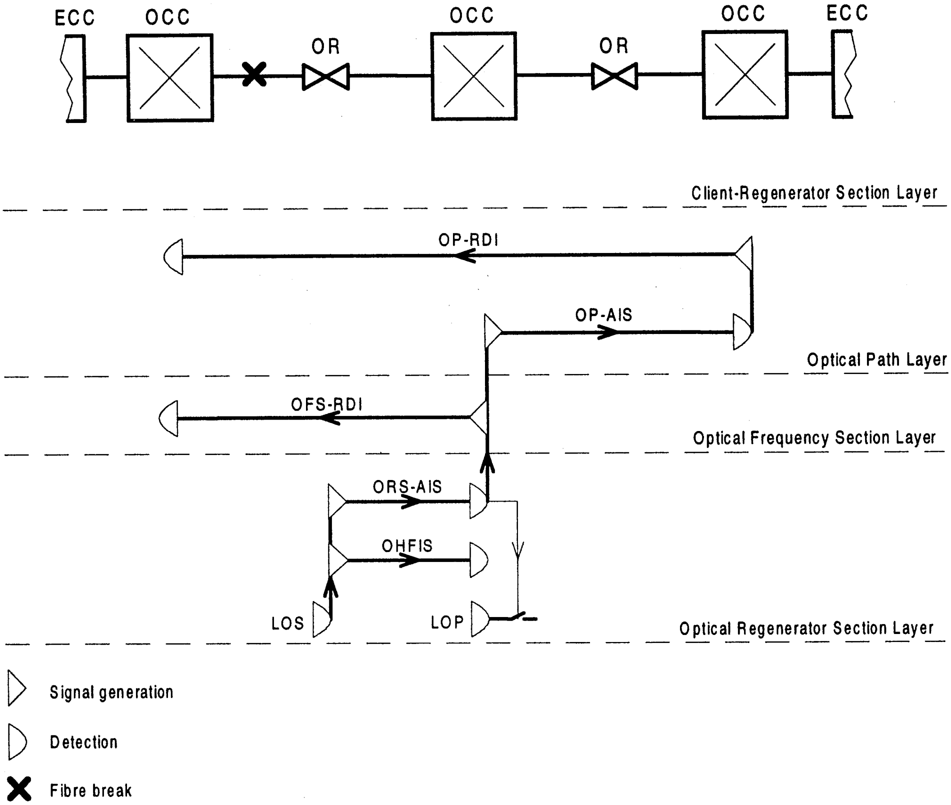


Figure 3: Maintenance signal flow and interaction

With the use of these signals and defect definitions it is not only possible to localise the failure in the optical transport network. But this information can also be used for protection mechanisms in the network which enhance the optical transport network availability.

Conclusions and Future Work

A means to enable failure localisation in the all-optical transport network is presented. This WDM supervision concept will be real-

ised within the ACTS projects PHOTON and MOON (Management Of Optical Networks) field trial. The MOON field trial will extend the PHOTON field trial with the appropriate network management which contributes to the aim of a complete OAM for optical transport networks.

But still work on the field of an OAM for optical transport networks has to be done. The presented concept concentrates on the supervision of the optical sections and the optical path. Extending supervision also to the optical nodes will lead to a comprehensive OAM concept for future all optical networks.

Optical transport network layered architecture for the MOONET

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Abstract

The layered network modelling, as defined in ITU G.805 [1], provides a means to describe, in a uniform way, the information transfer capability of the different transport networks, as well as, to deal with the inter-working and the management interoperability between the different transport networks. It provides a means to describe the network functionality in an abstract way in terms of a small number of architectural components.

The layering and partitioning concepts are used for the definition of the transport network layered architectures of the existing SDH network in G.803, and for the SDH-based ATM network defined in I.311. They are also applied to the optical transport networks. The standardisation of the layered architecture model for the optical networks described in ITU G.otn [2] is currently in progress, and some other models [4], [6] are also introduced. So far, the architecture proposed deals with the optical path network [6], which is characterised by the combination of WDM transmission and the wavelength routing.

The management of the optical path network is also in the scope of the project MOON (Management of Optical Networks) . MOON is one of the EC's ACTS projects with a task to establish a conceptual TMN framework for the management of all-optical WDM transport networks and to demon-

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strate the developed concepts and the feasibility of the adopted approach in a field trial network MOONET.

One of the main objectives of the project MOON is to elaborate the generic information model for all-optical WDM transport networks. For this task, the definition of the layered architecture model for the optical transport network is considered to be a starting point.

The layered architecture model covers all the technology aspects of the optical transport network. It can be used for equipment modelling, network access modelling, and the network resource modelling. For each layer network a managed process which interacts with its counter-part in the same layer or with the adjacent layer management processes can be defined. This process can be partly assigned to the adaptation and termination functions of the layer network. It must also provide an interface to the TMN agent. In this way the interaction of the OAM and the TMN can be modelled. The interaction between two different technology transport networks can be modelled with the interaction between management processes of two adjacent layer networks which belong to different technology transport networks.

In the project MOON the approach similar to the approach utilised in [5] is taken for the definition of the management information model. This comprises the utilisation of the adopted layered network architecture in modelling of the network elements and all-optical equipment, the identification of the network resources, and the definition of the related management capabilities.

The emerging management information model would be demonstrated in the field trial network MOONET. Due to the relatively simple topology of the MOONET not all of the concepts established in MOON could be verified. Still, the activities in the project MOON are aimed to give the contribution to the general view of the optical network modelling and management.

1 Introduction

The layered network modelling, as defined in ITU G.805 [1], provides a means to describe, in a uniform way, the information transfer capability of the different transport networks, as well as, to deal with the inter-working and the management interoperability between the different transport net-

works. It provides a means to describe the network functionality in an abstract way in terms of a small number of architectural components.

From the telecommunications management point of view, the layering and partitioning concepts as defined in the G.805 support transport network structuring into independent manageable parts.

The optical transport network can be decomposed into a number of independent layer networks , with a client/server relationship between adjacent layer networks.

The layering concept provide a means for the independent design and operation of each layer , but with the similar functions. This gives the possibility to encapsulate in each layer its own operations, diagnostic and automatic failure recovery , but still have the similar „look-and-feel“ in the management and operation of all layers.

On the other hand each layer network is uniquely identified with its information transfer capability, i.e. the input characteristic information it can adapt , which is relevant for the server role of the layer network, and its own , output, characteristic information related to its client role. So, the layering approach provides also, that the adding or modifying of a layer network can be done without affecting other layers from architectural viewpoint, provided that the characteristic information definition at its input and output is preserved. This should lead to the simple modelling of networks that contain multiple transport technologies.

The partitioning concept as defined in the G.805 is applied in order to define the network structure and domain or administrative boundaries in the network.

The topology of each layer network - the network structure, can be described by a means of the topological components, and the reference points[1]. The transparent information transfer across a topological component can be represented by a means of related transport entities[1]. In the sense of the network management these components represent network resources.

The layering and partitioning concepts are used for the definition of the transport network layered architectures of the existing SDH network in G.803, and for the SDH-based ATM network defined in I.311. They are also applied to the optical transport networks. The standardisation of the layered architecture model for the optical networks described in ITU G.otn [2] is currently in progress, and some other models [4], [6] are also introduced. So far, the architecture proposed deals with the optical path network [6],

which is characterised by the combination of WDM transmission and the wavelength routing.

The management of the optical path network is also in the scope of the project MOON (Management of Optical Networks) . MOON is one of the EC's ACTS projects with a task to establish a conceptual TMN framework for the management of all-optical WDM transport networks and to demonstrate the developed concepts and the feasibility of the adopted approach in a field trial network MOONET.

The field trial network, MOONET, will be a meshed network, with the all-optical core consisting of three optical cross-connects. From the aspect of the network element management, the management of the optical cross-connects and the optical line amplifiers included in one of the links will be demonstrated. No wavelength routing is supported in the network.

In the Figure 2-1 MOONET, the field trail network of the project MOON, is shown. The core network comprises three OXC located at the locations Passau and Schaerding. The MOONET represents both in respect of equipment and topology the extended field trial network of the project PHOTON.

One of the main objectives of the project MOON is to elaborate the generic information model for all-optical WDM transport networks. The management information model transforms the transport oriented network view concerned with network layers, optical paths, connections and trails, where the access- and termination-points and the adaptation functions are located in the network components and the equipment oriented network view concerned with network components such as terminal multiplexers, cross connects, add and drop multiplexers, and amplifiers, connected by fibre links carrying either single channel signals (SCS) supported by a lightwave with a distinct frequency, or multi channel signals (MCS), where each channel is supported by a lightwave of a different frequency, into a management view of a network, concerned with the managed objects which represent network resources.

For this task, the definition of the layered architecture model for the optical transport network is considered to be a starting point.

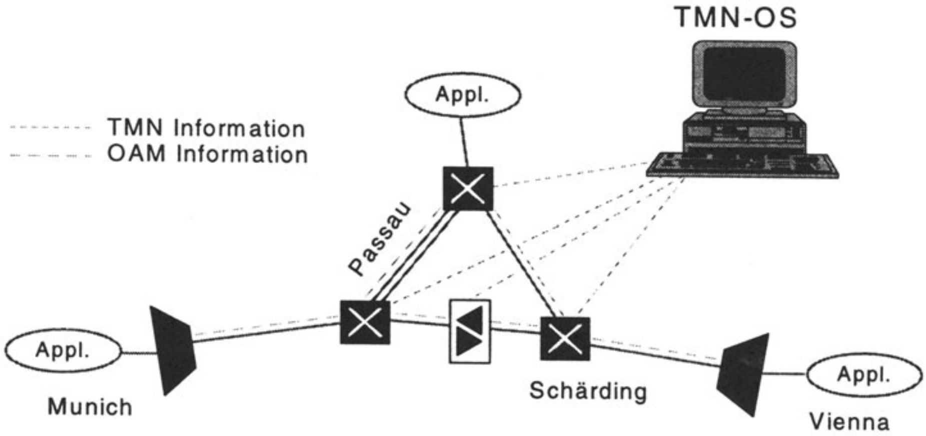


Fig. 1-1 MOONET

2 Technical approach

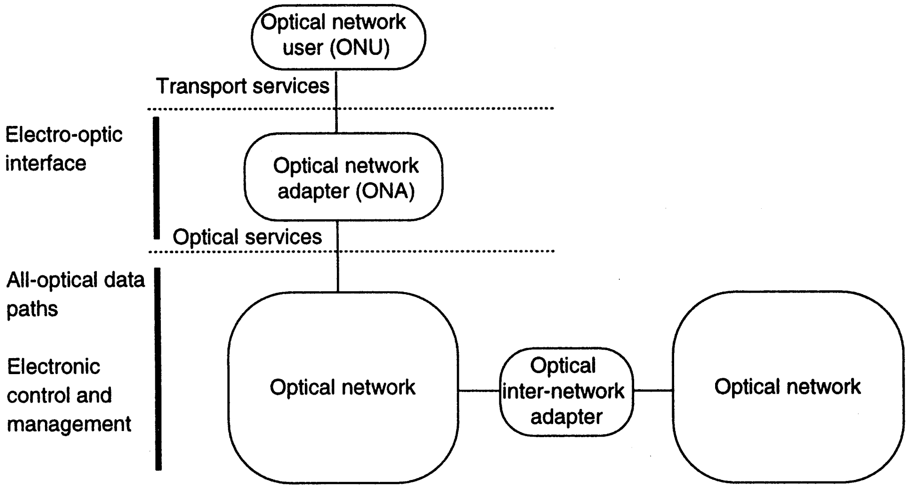
The architecture model for the optical network must provide answers for the set of questions such as:

- Where is the boundary of the optical network, what is the logical and physical content of the characteristic information on this boundary and of the characteristic information of each layer network,
- What is the transport and management content of the client/server relationship between layers, what is the „service" offered by each optical layer network and how this service is supported and guaranteed by a „protocol" specific for this layer network. This includes also the definition of the logical and physical content of the overhead information.

For the definition of the boundary of the optical network the model described in [7] and depicted in Fig. 2-1 is used. The model is enhanced with the optical inter-network adapter which should depict that possibly different optical networks could co-exist and should be able to interwork.

In the Fig. 2-1 the user of the optical network interact with the optical network through the optical network adapter. The optical network adapter provides the user with the transparent access to the networking capabilities of the optical network, and transforms the arbitrary user characteristic information in the optical signal, which can undergo all possible transformations in the all-optical network, such as frequency conversion, dispersion accommodation, regeneration, and still carry unmodified user information. Both of this aspects should find its representation in the transport network architecture model.

Inside the optical network only all-optical data paths exist with defined, and in the future standardised, logical and physical content. Two different optical networks which support different optical paths can inter-work through optical inter-network adapter .



taken from "Optical Services in Future Broadband Networks"
by Finn & Barry, IEEE Network, Nov/Dec 1996

Fig. 2-1 Optical network boundary

This paper shows how the layered network architecture model maps into this representation of the optical network. It also describes some of the considerations related to the layered architecture model such as the characteristic information, the client/server relationship between the adjacent layer networks and the overhead information.

3 Optical transport network layered architecture

The layering concept as defined in G.805 is applied to the optical WDM transport network in [2], [3] and [4] which resulted in several architecture models. All models , though slightly different introduce three new optical layer networks. These three new layers fully represent the management

capabilities offered in WDM optical transport network and should be sufficient for the purposes of TMN and network resources specification also in the project MOON. The architecture model currently used in the MOON resembles the G.otn model extending some aspects which are currently not covered. It is also one of the project objectives to take the G.otn model under consideration and to give comments according to the experiences gained in the project.

The model proposed in ITU-G.otn define three layer networks :

- optical channel layer,
- optical multiplex section layer and
- optical transmission section layer.

Most of the other models propose the term optical path layer instead of term optical channel layer. In the MOON the term „optical path „ is preferred to the term „optical channel" because it better describes end-to-end networking of the client signal and has no physical connotations.

The layered architecture model for the optical transport network :

- supports modelling of different optical equipment in the network,
- should fit into the existing layering scheme defined for the other transport technologies but should not be restricted only to them. In this way the simple modelling of networks that contains multiple transport technologies can be provided.
- encapsulate different transport and management capabilities in different layer networks .The optical path layer network support end-to-end networking of an arbitrary single optical signal. The multiplex section network support end-to-end networking of a multi-wavelength optical signal. The transmission section network support integrity of transmission on the optical media -fibre. Each layer network is characterised by its characteristic information.

In the Fig.3-1 the layer architecture model of the ITU-G.otn is used to describe the interconnection between optical path network user and optical path network. The models of the optical terminal multiplexer and the optical cross-connect are also shown.

The client network depicted in Fig.3-1 is the representation of the arbitrary network which can use services offered by the optical path layer network. The optical network adapter offers the transparent access to the networking capabilities of the optical network, and transforms the arbitrary user characteristic information into the optical signal. Due to this function, the optical path network adapter is placed at the boundary of the optical path network. The interfaces between the user , adapter and network can be physical (*2), (*3), (*5) or logical (1*), (*4). The existence of the logical interface implies that the two interconnected parts could be physically integrated. In the Fig. 3-1 some possible types of transport interconnections are shown.

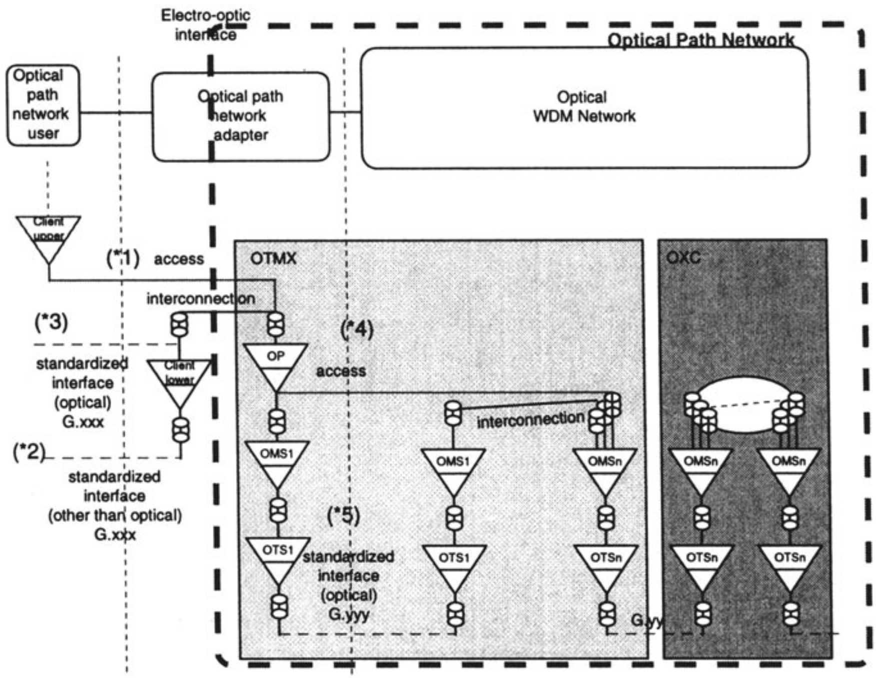


Fig. 3-1 Optical Path Network

The interface at the boundary of the optical path network supports the input characteristic information of the optical path layer network. The optical path layer network could in principle provide both optical and logical interface.

This means that the input characteristic information of the optical path layer can also have a physical representation. In the Fig. 3-1 the logical interface (*1) and the physical optical interface (*2) are depicted.

The interface (*5) is the physical interface between optical network adapter and optical network. It represents ITU-G.otn optical interface. The optical signal on this interface has the characteristic information of the optical transmission layer network and supports overhead and supervisory channels defined for all layer networks.

The interface (*4) depicts the logical interface between the optical network adapter and the optical network. In this case the adapter is integrated in the optical network equipment.

The architecture model of the client network comprises two layer networks, upper layer and lower layer. The lower layer of the client network is a kind of a physical media layer. We assume that between two client layer networks the logical interface exists - the output characteristic information of the upper layer has no physical representation.

The optical path layer network can be a server for this client layer network if the output characteristic information of the client layer is defined in the same way as the input characteristic information of the optical path layer network. In this case in the layering scheme the optical layer networks can be embedded under the client upper layer network. The ITU-G.otn model defines only the logical interface for the optical path layer network. Some other models propose that also the physical interface - single wavelength optical signal - should be supported. The interface (*3) depicts this case.

In this contexts the definition of the characteristic information, the overhead information and the client/server relationship for each layer network is the first important task.

3.1 Characteristic Information of the Optical Layer Networks

In the project MOON the definition of the characteristic information of the layer networks is adopted from the architecture models defined in [2] and in [4].

The characteristic information of an optical path layer network is a single wavelength optical signal with the optical frequency in defined wavelength range, power level in defined power level range, modulation bandwidth in defined bandwidth range. The signal is conditioned for the all-optical transport and supplemented by the optical path overhead information.

The characteristic information of an optical multiplex section layer network is an optical multi-wavelength signal with defined WDM grid, defined power level range, the restriction of group velocity dispersion, supplemented by an optical multiplex section layer overhead information.

The characteristic information of an optical transmission section layer network is an optical multi-wavelength signal of defined optical signal parameters such as power level, SNR, etc. supplemented by the overhead information.

The characteristic information of a layer network describes a resource which can be used for a transport of a client information. It should also define a resource for a transport of the overhead information of this layer network.

3.2 Overhead information and the concept of the supervision network

The overhead information definition represents a part of the „specific protocol" defined for one layer network, which guarantees the integrity of the transport of the client characteristic information. One part of the overhead information is the trail overhead information.

The trail overhead information is „added" to the adapted client characteristic in the trail termination source and „extracted" at the trail termination information sink. So according to this definition the overhead information is a part of the trail which is assigned to a single network connection.

This means that in the optical path layer network the optical path trail overhead must be transported embedded. The non-embedded overhead information - the overhead information carried by another optical channel is assigned to the different network connection, hence it does not belongs to the same trail. The optical multiplex section layer trail overhead information must be carried by a channel which belongs to the defined WDM grid. For the optical transmission section trail overhead information a channel which does not belongs the WDM grid can be utilised. The trail overhead information of one layer network is created, processed and terminated in that layer.

In the optical network the concept of the supervision network for transport of the trail overhead information of the multiplex and transmission layer network as well as the overhead information which is not related to the trail, such as OAM data used for the alarm suppressing purposes (inter-level alarming) and for the control of the automatic OAM actions e.g. automatic protection switching, can be introduced. The supervision network can be a standardised part of the transport optical network architecture as proposed in ITU-G.otn. In this case the optical transmission layer provides access point for the supervision information of all layers. This information has a logical interpretation in its containing layer and becomes its physical interpretation in the optical transmission layer which provides network connection for a supervision network. The establishment and monitoring of the supervision network connection is also performed in the optical transmission layer.

The standardised layered architecture model for the optical network should be applicable for the modelling of the arbitrary optical WDM network. Still, when it comprises also the definition of the overhead channels or the supervisory network it puts restrictions on the modelling of some optical equipment. Some very simple optical equipment can not be modelled with this, because it supports no termination points of the supervision network where supervision data could be accessed.

Hence, it could be assumed that in the future some parts of the network will not support the whole standardised functionality, the transport of the supervision data in the first place, but can still be used for the transport. The layer network in which the supervision network connection is established and monitored has to be able to deal with this exceptional situation.

3.3 Client/Server Relationship

The transport of the client information is the „service“ offered by a layer network which is supported and guaranteed by a „protocol“ specific for this layer network.

The service defines how the characteristic information of the client network can be adapted and enhanced to form the characteristic information of the server network. This comprises the definition of transport processing functions: adaptation and termination function and the definition of the overhead information.

The protocol comprises

- the definition of the two counter-part management processes in the same layer and the information they exchange. This can be related to the definition of the termination function. The information exchanged cab is a part of the layer network trail overhead information, and can be transported in the layer network overhead.
- the definition of management processes in two adjacent layers and the information they exchange. This can be related to the definition of the adaptation function. The adaptation function has access to the original characteristic information of the client, which means that it can also have an access to the client overhead information.

3.3.1. Adaptation function

The adaptation function is a „transport processing function“ which adapts client to the requirement and limitation of the server layer. It defines the „server/client“ association between the client layer connection point and server layer access point, which delimit the adaptation function.

The transport related functions of the adaptation function for all three layer networks are defined in the ITU-G.otn and should be only enhanced for the case when the optical path layer network also excepts an optical signal.

The management related functions of the adaptation function can be described as follows:

- The adaptation sink performs monitoring of the client connections when a multiple of client connections are transported over a single trail in server network. This is the case in the optical multiplex section layer and it includes loss of channel, charier wavelength shift, degradation of the signal quality.
- The adaptation sink generates supervision information (OAM data such AIS, etc.) to be sent to the client layer network trail termination sink.

3.3.2. Trail termination function

The trail termination function is a „transport processing function“ which generates the characteristic information of the layer network and ensures integrity of that characteristic information. The trail termination defines the association between the access point and the termination connection point, which delimit the trail termination function.

The transport related functions of the trail termination function can be described as follows.

- The trail termination source accepts adapted client characteristic information, creates trail overhead and assigns it to an associated network connection.
- The trail termination sink terminates the trail, terminates the trail overhead information and passes the adapted client characteristic information to the adaptation function.

The management related functions are described as follows:

- The trail termination source generates supervision information (OAM data such as remote defect indication in all layer networks or shift of frequency degradation in the optical multiplex layer network, etc.) to be sent to its counter-part trail termination sink
- The trail termination sink performs validation of the trail overhead,
- The trail termination sink performs assessment of transmission quality of the characteristic information, fault detection and alarming,

- The trail termination sink process supervision information received from its counter part or a server layer network (when monitoring of the connections is done in the server layer network).

4. Layer Network Management Processes

The management process in one layer network is concerned (1) with the normal operation of the resources of layer network including automatic processes such as resource status monitoring, protection switching, alarm detection ,automatic alarm suppressing, fault localisation and (2) it should support the interface to the TMN management system.

The management processes in different layer networks can communicate in several different ways. The client layer network management process can supply its management information to the server layer network management process, or to its distinct counter-part

- as part of its own characteristic information
- as an information carried by the supervisory network
- directly , when the processes are collocated in the single agent

Two management process can also communicate only with a management system, and not with each other. In this case their relationship and correlation of the supplied information are managed by the manager.

The access point represents the boundary between two different layer networks where the client information enters and leaves the server network. Between two network access points the connection in the server network is established and two different management processes are related to it :

- the management process in the client network which requires the establishment of the connection, relates two access points and provides the unique identification of the client to the server
- the supportive management process in the server network. This process performs monitoring of the connection integrity by a means of trail monitoring or connection monitoring, alarm detection, etc.

Here we will only discuss connection monitoring.

As stated in [2] the integrity of the information transferred over connection can be monitored using one of the techniques: (1) inherent monitoring , using the data inherently available from the trail in the server layer network,

(2) non-intrusive monitoring, by use of listen only monitoring of the original client characteristic information, (3) intrusive monitoring, by breaking the original trail and introducing a test trail that extends over the part of the connection of interest for the duration of the test, and (4) sublayer monitoring, by a trail created in a sublayer.

For the monitoring of the optical client network connection and optical multiplex section connections the inherent monitoring can be applied.

Since the adaptation function in the optical multiplex section layer includes multiplexing the error performance of each link connection in an optical path layer supported by a trail will not be available individually, so for the monitoring of the optical path connections the non-intrusive monitoring must be applied. The listen only monitoring of the characteristic information of the optical path layer network is performed in the optical multiplex section layer connection point , and includes:

- monitoring of the demultiplexed WDM channels
- non-intrusively reading of the optical path overhead information related to monitored channels in order to relate the defects detected for the WDM channels to the unique optical path identifier.

In the definition of the management information model the part of the layer network management process which is concerned with the trail monitoring (inherent characteristic information monitoring) is assigned to the managed object termination connection point of the layer network.

The non intrusive connection monitoring is assigned to the managed object connection termination point between client and server layer where the related connections are accessible before they are being multiplexed in the server layer.

Other aspects, such as protection switching , etc. are also covered by the management information model of the project MOON and will be demonstrated in MOONET.

5. Layer Network Resources

In the sense of the network management G.805 architectural components represent network resources. Since they are defined in general way in [2], in the standard I-ETS 300-653 [5] the attempt was made to define, in the general way, also the related managed objects and management capabilities.

The topological components describe network resources in the domain of the static configuration resource management. Static resource management is mainly concerned with the provisioning of the resources such as the provisioning of a layer network and characteristic information, the provisioning of access points, the provisioning of access groups, the configuration of access groups, the provisioning and the configuration of connection points, the provisioning and configuration of subnetworks and links.

The transport entities describe network resources in the domain of the dynamic configuration connection management that is concerned with the set-up, modification and release of connections such as sub-network connection set-up, the release of sub-network connections, sub-network configuration, scheduling, trail set-up and release, the setting-up of network connections, which comprises: the configuration of the link, the provisioning of link connections and tandem connection provisioning and configuration, and the release of network connections.

The Figure 5-1 depicts the whole set of the G.805 architectural components.

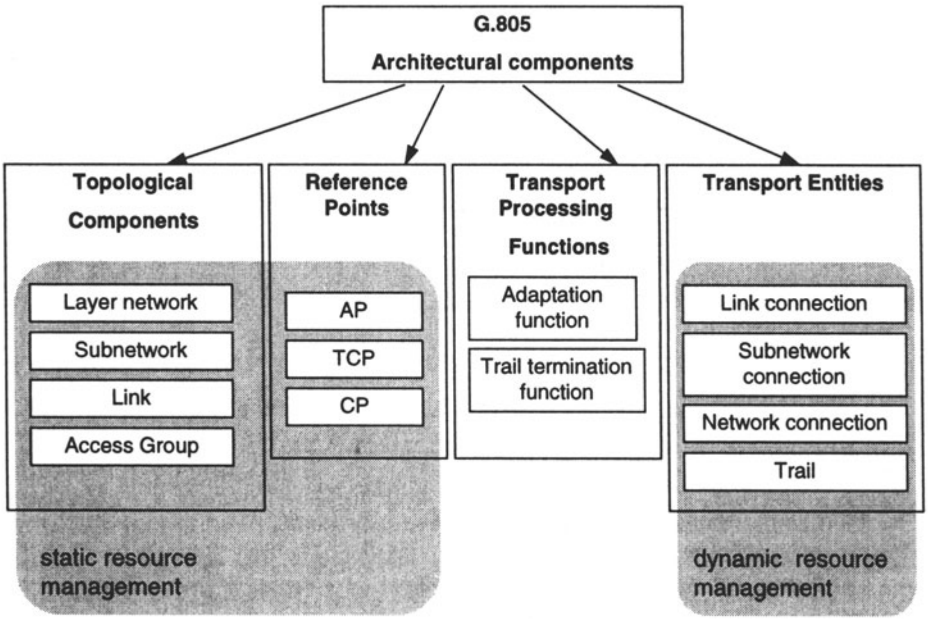


Fig. 5-1 G.805 Architectural components

In the project MOON the approach similar to the approach utilised in [5] is taken for the definition of the management information model. This comprises the utilisation of the adopted layered network architecture in modelling of the network elements and all-optical equipment, the identification of the network resources, and the definition of the related management capabilities.

Within one layer network all resources can be described with the architectural components defined within this layer. In the table in Fig. 5-2 the components that can be considered to represent network resources in different optical transport layer networks are depicted. The symbol (*) depicts that this component is used to describe the resources of the MOONET.

Topological component	Defined for a layer network			Transport entity	Defined for a layer network		
	OP	OMS	OTS		OP	OMS	OTS
Layer network	X (*)	X (*)	X (*)	Link connection	X (*)	X (*)	X (*)
Sub-network	X (*)	X	-	Sub-network connection	X (*)	X	-
Link	X	X	X (*)	Network connection	X	X	X
Access group	X (*)	-	-	Trail	X (*)	X (*)	X (*)
Access point	X (*)	X (*)	X (*)				
Connection point	X (*)	X (*)	X (*)				

Fig. 5-2 Network resources

The subnetwork and subnetwork connection are defined for both optical path and optical multiplex section layer. This represents both end-to-end networking of the client signal and WDM signal. The access group is defined only for optical path layer where collocated optical signals are multiplexed in the same link (same fibre).

The emerging management information model would be demonstrated in the field trial network MOONET. Due to the relatively simple topology of the MOONET not all of the concepts established in MOON could be verified.

Still, the activities in the project MOON are aimed to give the contribution to the general view of the optical network modelling and management.

6. Conclusions

The layered architecture model covers all the technology aspects of the optical transport network. It can be used for equipment modelling, network access modelling, and the network resource modelling. For each layer network a managed process which interacts with its counter-part in the same layer or with the adjacent layer management processes can be defined. This process can be partly assigned to the adaptation and termination functions of the layer network. It must also provide an interface to the TMN agent. In this way the interaction of the OAM and the TMN can be modelled. The interaction between two different technology transport networks can be modelled with the interaction between management processes of two adjacent layer networks which belong to different technology transport networks. In the project MOON the optical transport network layered architecture is used as the starting point for the definition of the TMN resources, and of the related TMN management information model.

Acknowledgement

The optical transport network layered architecture is a topic of main a interest for a number of partners participating in the project MOON. It has been recognised that the layered architecture model should be the basis for the management considerations, so many discussions and consultations started, and are still in progress. The author, who is actively participating in the team responsible for the definition of the information model for the optical network management in the project MOON, took also part in this discussions and contributed the project intern workshop which aimed to enlighten this topic from many different points and to tackle many different aspects such as the necessity to establish a model able to represent also network elements such as 2R and 3R regenerators, different client interconnections etc. This paper evolved from the contribution of the management information model team to this workshop. The author would like to mention all MOON partners who are currently engaged and contributing to this topic : CSELT Italy, DT Germany, Siemens Germany and Siemens Austria.

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PART TWO

Network planning and design

3

New directions in modelling, analysis and design of WDM/OFDM-networks: (I) Optical Switching

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Abstract

Bearing in mind that a topological representation of a finite graph is a compact space, by the relationships between (Graph)Topology, Algebraic Topology, Group Theory, (Differential)Geometry and Combinatorics a new universe arises for modelling, analysis and design of (telecommunication) networks. Throughout the present paper, coverings/covering spaces, the lifting problem and quotient graphs are briefly interpreted in terms of the requirements for the combinatorial design of optical switches though the presentation is mainly based on illustrations rather than on a (precise) mathematical description.

Key words: Multi-layer, parallel waveguides, electrodes, spatial all-optical switch, planar all-optical switch, all-optical expander/concentrator, parallel permuters, vertical stacking, graph covering, lifting

1. Introduction

Graph models are fundamental tools in modelling, analysis and design of communication networks. Mathematicians have recognized the limitations of ordinary graph models and developed several generalizations such as pseudographs and hypergraphs, respectively. Pseudographs are multigraphs (≡multiple edges between some nodes) with (multiple) self-loops. For example, the de Bruijn directed graph (digraph) $B(\Delta, D)$ with D edges between every node-pair and self-loops at some nodes provides the nonblocking simultaneous communication of the node-pairs [1]. In contrast, hypergraphs are graphs with more than two nodes for every edge [2]. Pseudographs may be applied to model WDM/OFDM-networks consisting of optical fibers interconnecting optical nodes and access nodes (physical layer), respectively. By the partition of access nodes into intersecting subnets a hypergraph is formed (logical layer) [3].

Throughout the paper, a topological approach is applied where finite simple regular graphs (and even infinite, nonregular, multigraphs, pseudographs or hypergraphs) are the most simplest space [4]. The next more complicated topological spaces are (compact) surfaces which are of interest once pseudographs are embedded into them. One basic problem of topology is to determine whether there exits a continuos function (and its inverse) between two given topological spaces. Therefore, topology is, roughly speaking, called the geometry of continuous functions. Here the concept of covering projections/covering spaces and of quotient maps/quotient spaces comes in. Throughout an application of topology to networks, these geometric problems have to be treated by means of powerful algebraic methods. The aim of the ongoing work is to deduce some valuable hints for the modelling, analysis and design of WDM/OFDM-networks and their components.

Throughout the paper the application of graph coverings is shown for the design of all-optical switches, expanders and concentrators. However, the most convenient treatment of graph coverings is by voltage graphs [5] which will not be shown in this paper. Another problem are liftings which are briefly mentioned throughout the discussion of switches, expanders and concentrators.

Optical Network Design and Modelling H. van As & A. Jukan (Eds.)

2. Preliminaries

In the following minor elements from topology [4] and graph theory [5] are collected which are needed to understand the ideas of the paper.

2.1 Graph topology

From the point of view of topology, a graph/network is a rather simple topological space even it may be an infinite, nonregular pseudograph. Note, a topological space $(X, \mathcal{A})$ is a topology $\mathcal{A}$ on a set X where $\mathcal{A}$ represents a family of subsets of X which satisfies some simple conditions [4].

Coverings

A family $\mathcal{A}$ of subsets A_i of X is said to cover X if and only if (iff) $\bigcup A_i = X$. In terms of graph theory, a graph G is a covering of a graph H iff there exist a map $p : V(G) \longrightarrow V(H)$ which induces a one-to-one correspondence between the nodes adjacent to $v \varepsilon G$ and the nodes adjacent to $p(v) \varepsilon H$. Then the graph G is called the derived graph [5] or the covering space [4].

Example 1: The distance-transitive graph/antipodal graph $C_4^{(2)}$ (Sub-Section 2.2) in Fig. 1 (a) lhs, which equals the 3-cube Q_3 [6], is a double cover of K_4 [Fig. 1 (a) rhs], i.e. K_4 is contained in Q_3 with respect to both coordinates [7]. Note, K_4 covers the ring C_4 which represents the intersection of the embedded 4-gon prism (Sub-Section 3.2).

Example 2: The bipartite graph $K_{3,3}$ and $C_3^{(2)}$ (two connected triangles) both have the same degree. Then there exist a graph $C_6^{(2)}$ (two connected hexagons) which cover both subgraphs [8].

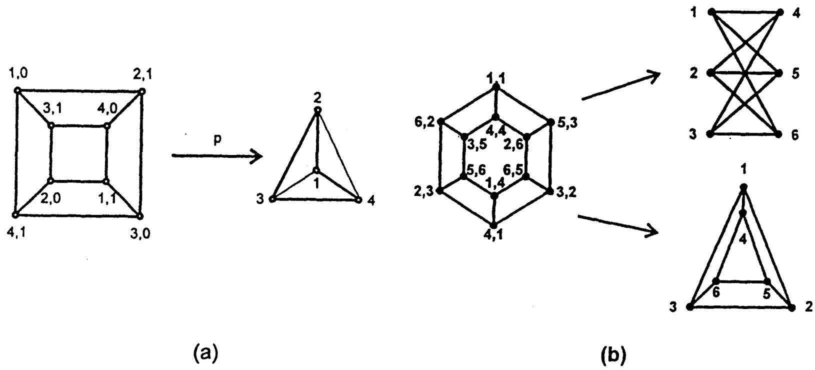


Fig. 1. Double covers of graphs. (a) The two connected cycles $C_4^{(2)}$ ($\equiv Q_3$) cover the completely connected graph K_4 twice (Example 1). (b) $C_6^{(2)}$ covers the bipartite graph $K_{3,3}$ and $C_3^{(2)}$ (Example 2).

Lifting

The lifting problem in topology is to decide when one can 'lift' a projection/map $f : W \longrightarrow H$ to a map $g : W \longrightarrow G$ where $p : G \longrightarrow H$ is given [Fig. 2 a)]. Similar, the various nonisomorphic coverings are connected by an automorphism which also can be lifted [Fig. 2 (b)]. Liftings may be applied to mappings/projections of topological spaces (graphs/networks or walks/circuits e.g. the boundary of faces [4,5]) by first embedd the pojected graph H and then lift the embedding such that the covering space G is embedded [4,5,9].

Remark 1: By the lifting concept, walks/routings in an N-gon prism switch (Sub-Section 3.1) may be lifted to walks/routings in an embedded mN-gon prism switch (Sub-Section 3.2) and vice versa, walks/routings in the mN-gon prism switch may be based on walks/routings in an N-gon prism switch. However, presently, the routing of the mN-gon prism switch for the rearrangeable nonblocking case is redrawn from an algorithm for cellular arrays [10,11].

$$\begin{tikzcd} & G \arrow[d, "p"] \\ W \arrow[ur, dashed, "g"] \arrow[r, "f"] & H \end{tikzcd}$$

(a)

$$\begin{tikzcd} G \arrow[r, "\beta"] \arrow[d, "p"] & G \arrow[d, "p"] \\ H \arrow[r, "\alpha"] & H \end{tikzcd}$$

(b)

Fig. 2. (a) Lifting of a mapping f by means of the covering projection p to $g = p^{-1} \circ f$ [4]. (b) Connection of nonisomorphic coverings by a lifted automorphism, i.e. the automorphism α is lifted to the automorphism β [12].

2.2 Graph theory

The paper deals with distance-transitive graphs, which are the most symmetric graphs, and some definitions and results, which mainly are due to [13], are collected in the following.

Automorphism

An automorphism of a (simple) graph $G = (V, E)$ (where V is the set of nodes and E the set of edges) is a permutation π of V which has the property that (u, v) is an edge of G iff $(\pi(u), \pi(v))$ is an edge of G, i.e. it preserves adjacency.

Distance-transitive graph

A graph $G = (V, E)$ is said to be distance-transitive, if, for any nodes $x, y, u, v \epsilon V$ satisfying $d(u, v) = d(x, y)$ (d is the distance between 2 nodes in terms of the number of edges) there is an automorphism π of G which takes u to v and x to y. This is the strongest symmetry condition on graphs which allows to reduce its description by the $N \times N$-adjacency matrix via the description by an $3 \times D+1$-intersection array to a $D+1 \times D+1$-matrix (D is the diameter) where all the three matrices have the same eigenvalues. Here an interesting eigenvalue problem comes in [14].

Antipodal graph

An antipodal graph G with diameter D has the property that each node $v \epsilon G$ has an unique (antipodal) node $\overline{v}$ of distance D from v in G. The antipodal node-pairs in G produce a quotient graph H with a double cover projection $p : G \longrightarrow H$ (Sub-Section 2.1). Any antipodal graph G has circuits of length $2D$ passing through antipodal node-pairs [15]. Here the 'block system' of a graph comes in, which allows to derive a quotient graph whose nodes correspond with the blocks (Note the intersection of the embedded mN-gon prism switches in Sub-Section 3.2 are antipodal graphs).

Example 3: The completely connected graph K_4 in Fig. 1 (a) is a graph quotient of the 3-cube Q_3 and the double triangle $C_3^{(2)}$ in Fig. 1 (b) is the graph quotient of the double hexagon $C_6^{(2)}$. Roughly speaking, the N-gon is a quotient of the N+1-gon.

3. Concepts and quantities

In the following, the elements of the foregoing Section are applied to some novel components of WDM/OFDM-networks. Although there has been obtained a considerable progress in glas fiber research applications, the crucial points are the nodes of the networks which include optical switches and crossconnects ($\equiv$ a space switch carrying frequency channels), respectively. The space switches presented in the following are aimed to be extended to crossconnects.

3.1 The N-gon prism switch

For the purpose of the extension of current all-optical switching principles [16] into the 3-D physical space, the N-gon prism switch ($N \geq 3$) has been introduced which is based on multi-layer architectures and nearest-neighbour interconnected 2x2-switches [17,18,19] (see Fig. 3 for N=4).

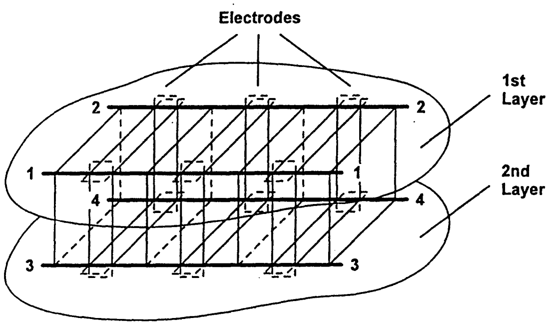


Fig. 3. 3-stage 4-gon prism switch composed of a double-layer, parallel waveguides and electrodes.

The architecture of the N-gon prism switch is described for one stage by [20]

$$C_N \oplus K_2 \tag{1}$$

where $\oplus$ is the Kronecker sum (KS) [21], C_N is a cycle with N nodes and edges and K_2 represents 2 nodes interconnected by one edge. The number of stages (NS), sufficient for the generation of $N!$ (arbitrary) permutations ($\equiv$ rearrangeable nonblocking interconnections) is

$$NS = N - 1 \tag{2}$$

caused by the isomorphism between the N-gon and the nearest-neighbour interconnection of switches with skew 1 (Fig. 4) [22].

The number of switches per stage (NSW_{stage}) is

$$NSW_{stage} = \lfloor \frac{N}{2} \rfloor \tag{3}$$

where the 'floor' function $\lfloor a \rfloor$ is the largest integer less than or equal to a. From Eqs.(2) and (3) we may conclude that the total number of 2x2-switches is

$$NSW_{total} = \lfloor \frac{N}{2} \rfloor (N-1) \tag{4}$$

which is below the Spanke-Benes minimum $N(N-1)/2$ for N odd.

For the proper understanding of the N-gon prism switch the following assumptions are important

(A) Once a 2×2-switch is formed, no further switch may be established within the same stage with the waveguide involved in this 2×2-switch and

(B) Spatial diagonal switching is not allowed and is resolved by diagonal switching at the boundary faces/facets of the N-gon prism.

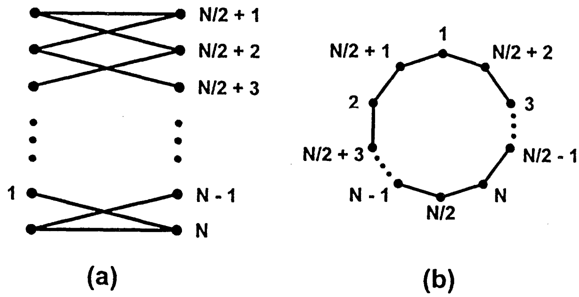


Fig. 4. Isomorphism between (a) nearest-neighbour interconnections and (b) N-gon.

From the switching principles (A) and (B) we may conclude that the moving location of switches (SW), expressed by the number of their possible arrangement ($NPASW$) within the N-gon prism switch, determines the improvement in Eqs.(2) and (4) compared with the Spanke-Benes network. $NPASW$ is shown for some $N \geq 3$ in the following Table 1 and Fig. 5.

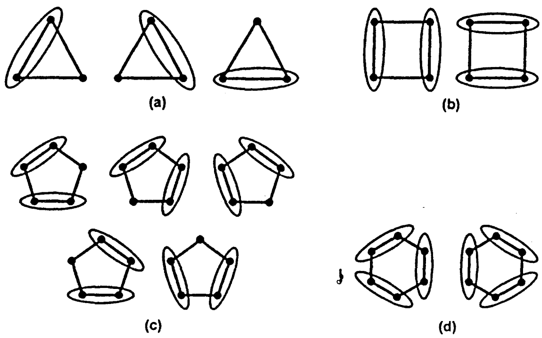


Fig. 5. Possible arrangements of 2×2-switches for (a) N=5 to (b) N=6.

Table 1. Number of possible arrangements of 2×2-switches at one stage of the N-gon prism switch.

N	3	4	5	6	7	8	9	10
$NPASW$	3	2	5	2	2	2	2	2

Example 4: For N=3 the Spanke-Benes network has 3 stages and 3 switches which provides 2^3=8

states sufficient to generate 3!=6 permutations [16]. However, the 3-gon prism switch contains 2 switches and is thus represented by 2^2=4 states which is not enough to generate 6 permutations. But, according to Table 1, the number of possible states is 3x4=12 which now is sufficient.

Remark 2: In Table 1 ,the case N=5 has the largest $NPASW$ (Fig. 5), though no advantage seems to arise in Eq.(4).

Remark 3: The routing algorithm of the N-gon prism switch is of complexity $O(N)$ and is optimal [11].

3.2 The embedded N-gon prism switch

Increasing the number of inputs/outputs, the number of layers increases, which, however, may be difficult to set up. Therefore, embedded prism switches are introduced which are expected to be implemented without additional electrodes for switching between the prisms (Fig. 6).

Table 2. Reduction of the average distance $\bar{d}$ by the (connected) embedding of prisms.

N	6	8	9	10	12	14	16
N-gon	1.50	2.28	2.50	2.77	3.27	3.76	4.26
3-gon$^{\nu}$	1.4^2		1.87^3		2.36^4		
4-gon$^{\nu}$		1.71^2			2.18^3		2.27^4

ν means the number of prisms

With the architecture in Fig. 6, for a large number of inputs (e.g. N=16), we need 8 layers [Fig. 7 (a)]. For the further reduction of the number of layers we may implement the prism switch in Fig. 7 (b) [23] or the 4-gon^2 prism switch (synonym: 2x4-gon prism switch) which may be found by (1) line iteration of Fig. 6 (b) or as an embedding into the Kautz digraph $K(2,4)$ [24].

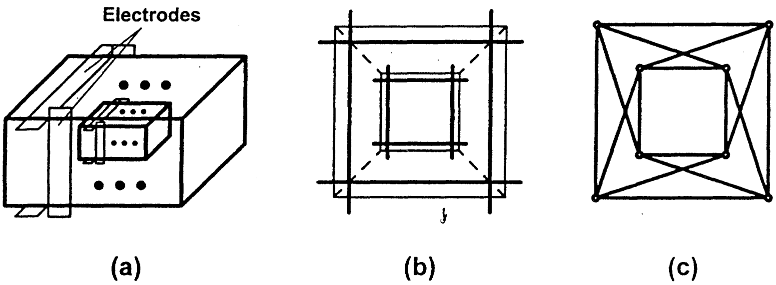


Fig. 6. (a) Proposed implementation of the embededd 4-gon prism switch. (b) Intersection. (c) Generalization (which might be difficult to implement except in the planar case).

The embedding of one prism reduces the average distance between arbitrary node-pairs (Table 2) and in turn NS for rearrangeable nonblocking interconnections. However, the available routing algorithms show that NS increases considerably for $\nu(=m)\geq3$ though the obtained results may not represent the minimum [11].

From an analysis of the average distance $\bar{d}$ we may conclude an increase of the average distance $\bar{d}$ and in turn of NS for a decreasing number of layers (Table 3).

Remark 4: The topology of Fig. 7 (a) equals the hypercube Q_4 except the absence of the interconnections between the outer and inner square in the latter [6]. For $N \geq 5$ and $\nu(=m)=2$ the numbering of the nodes may be according to the dihedral group [25].

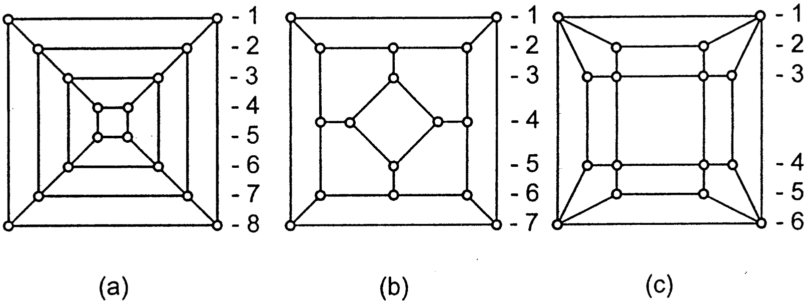


Fig. 7. Intersection of embedded prism switches. (a) 4-gon[4] prism switch. (b) Redrawn from [23,Fig. 13]. (c) Redrawn from [24,Fig. 2]. (The digits count the number of layers.)

Table 3. Characterization of distance-transitive graphs (arising by the intersection of embedded prism switches) by the number of layers and by the average distance $\bar{d}$ [the 1st, 2nd and 3rd column is the architecture in Fig. 7 (a),(b) and (c)].

No. of Layers	8	7	6
$\bar{d}$	2.27	2.46	2.73

Example 5: For the 3-gon^2 prism switch (6 inputs/outputs) NS=4 for providing rearrangeable nonblocking interconnections instead of 5 stages for the 6-gon prism switch. For the 4-gon^2 prism switch (8 inputs/outputs) NS=5 instead of 7 stages for the 8-gon prism switch.

Remark 5: The latter NS=5 equals the (global) shuffle result 2log8-1 (lower bound) which always arises iff the intersection graph is a hypercube and which is, after our knowledge, the minimum NS for (local) networks of nearest-neighbour interconnected 2x2-switches.

Remark 6: The development of a routing algorithm for the embedding of m-1 prism switches ($m \geq 2$) is ongoing work. For example, for two 4-gon prisms (8 inputs/outputs in Fig. 6) a branch-and-bound-based algorithm is under development [11].

3.3 Planar N-gon switches

The presented multi-layer architectures offer novel all-optical switching fabrics. However, setting up multi-layer architectures may be difficult. Thus their planar realization is desired which is briefly shown in the following by means of the N-gon prism switch. Caused by assumptions (**A**) and (**B**), for N inputs/outputs, the number of waveguides is N+1 (Example 6). However, the doubled waveguide may be chosen arbitrarely out of the N waveguides (Fig. 8) and a path selection switch has to be located at the end of the parallel waveguides (Figs. 9 and 10).

Example 6: For N=3 the sitation is obvious whereas for N=4 we may switch between the waveguides 1 and 2, 1 and 3, 2 and 4 and 3 and 4 (spatial diagonal switching between 1 and 4 and 2

and 3 is not allowed).

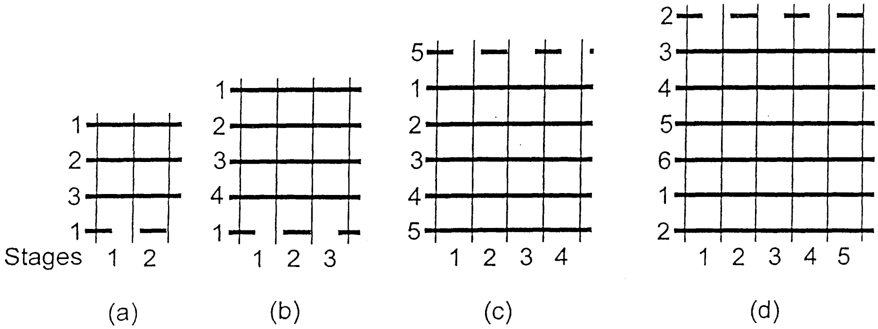


Fig. 8. Schemes for the planar realization of N-gon prism switches for $3 \leq N \leq 6$ (solid lines are common waveguides, dashed lines are additional waveguides where the latter may cause crossings at the inputs and outputs). In principle, any of the N waveguides may be doubled which is verified in Fig. 8 (c) and (d).

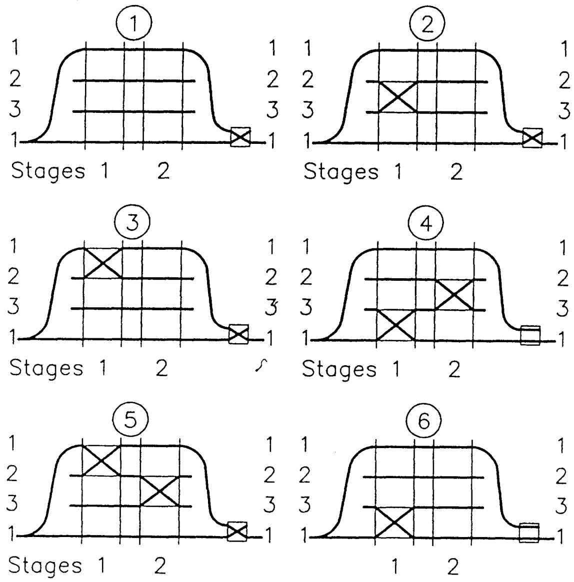


Fig. 9. The $3!=6$ permutations of the planar 3-gon prism switch. Note without the doubled waveguide, $NS=3$ for the rearrangeable nonblocking case which equals the Spanke-Benes network result [16].

Assumption (**A**), which is implicitely satisfied in the multi-layer architecture, has to be taken into account by the switch setting algorithm. For example, for N=3, if a switch is established between waveguide 1 and 2, within the same stage, no further switch may set up. In contrast, assumption (**B**), is considered by the number of waveguides and their particular arrangement.

Remark 7: From a comparison of planar N-gon prism switches (Figs. 8 to 10) with the Spanke-Benes network [16] we may conclude a saving of 1 stage (NS = N-1 instead of N) and less switches for an odd N according to Eq.(4). However, the prize is an additional waveguide and a path selection switch.

Example 7: For the planar 6-gon prism switch with 5 stages, the number of 15 switches is established by means of 7 parallel waveguides (Fig. 8) and one path selection switch (Figs. 9 and 10) whereas for the embedded 3-gon^2 prism switch (6 inputs/outputs) we have 4 stages, the number of 12 parallel waveguides and and an additional stage with the number of six 2×2-path selection switches where crossings arise.

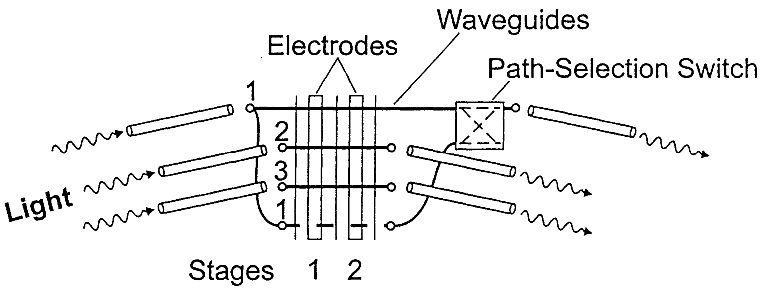


Fig. 10. Scheme of a planar 3-gon prism switch (2 stages, 1 switch/stage, 4 waveguides and 1 path selection switch) instead of the 3 stages and 3 switches of the Spanke-Benes networks [16].

Remark 8: All the proposed multi-layer switching architectures may be realized, in principle, in a planar manner (Sub-Section 3.3) where trade-offs arise between the parallelism (of waveguides) and NS and the number of crossings.

3.4 All-optical $O(1)$-switches

The increase of the number of inputs/outputs of N-gon prism switches demands (1) an increase of the number of layers which, by means of the current technology, may be difficult to set up and (2) causes a large NS and in turn a high attenuation of signals. Therefore, the (coset) decomposition of the N! permutations by means of several m-permuters (m-gon prism switches, $m \leq N$), as a starting point [26], is a practical solution once the number of permuters is reduced to the minimum [19].

Remark 9: Note the decrease of the number of permuters increases the complexity of the routing in the shells. Beside the reduction of the parallelism, a further problem is the organization of the shells at the lhs and rhs of the parallel m-permuters. Three attempts, different also from the point of view of technology, are possible: (a) free-space interconnections (b) cellular arrays (c) expanders and concentrators (Sub-Section 3.5).

Remark 10: By means of (a), the $O(1)$-switch arises in straight-forward way. However, (b) and (c)

cause additional stages for the expander and concentrator and thus compete with the N-gon prism switch.

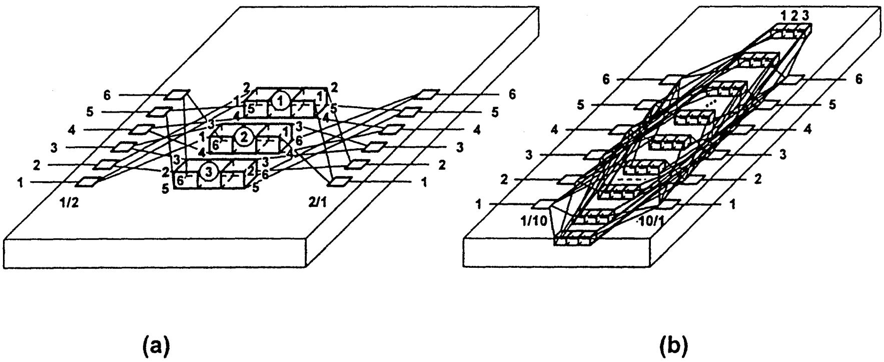


Fig. 11. All-optical $O(1)$-switches for 6 inputs/outputs. (a) Rearrangeable nonblocking interconnections [19]. (b) Circuit switching mode [17].

3.5 Expanders and concentrators

The distance-transitive graphs [13] may also be applied for the design of all-optical expanders and concentrators. In this way we may organize the shells at the lhs and rhs of the parallel stacked permuters according to the solution (c) (Sub-Section 3.4).

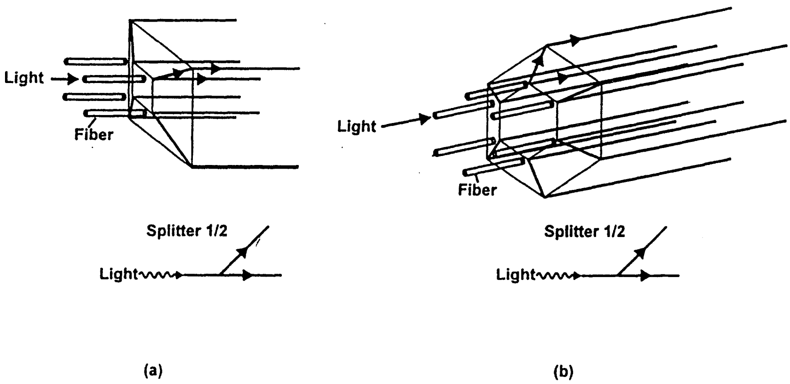
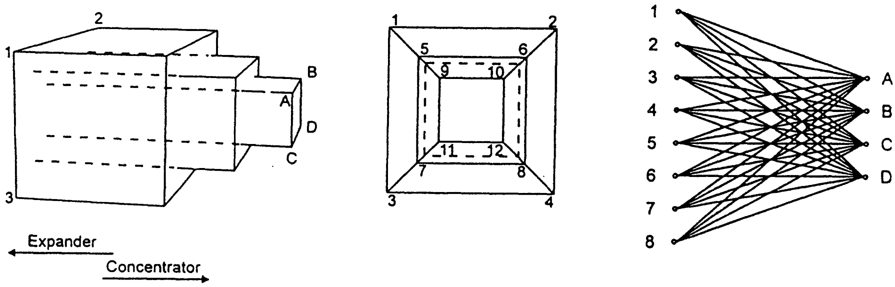


Fig. 12. Scheme of all-optical expanders (a) 4/8 and (b) 6/12 at the input of an all-optical switch (the reversal is the concentrator at the output of a switch).

The splitting principle of a simple expander is shown in Fig. 12. There the glas fibers carry the light/data to the waveguides which are splitted 1:2 (1:2 also for the 6×6-switch in Fig. 11, however, 1:3 for an 8×8-switch) and which forward the light to the three 4-permuters [Fig. 11 (a)]. The

outputs of the three 4-permuters [Fig. 11 (a)] are combined in the concentrator (Fig. 13) which finally forward the light/data to the output of the switch.



(a) (b) (c)

Fig. 13. (a) Scheme of an expander and concentrator. (b) Intersection. (c) Bipartite graph representing the area between the largest (outer) square and the dashed lined square.

Remark 11: All-optical expanders/concentrators may also be realized in a planar manner (Figs. 8 to 10).

4. Design principles

Large optical switches usually are designed by the substitution of networks of smaller switches. However, in this way, NS and in turn the attenuation of signals passing through the network increases considerably. Therefore attempts are desired which allow to leave this substitution principle and arrive at proper operating all-optical switches with a large number of inputs/outputs and small NS. Once we apply multi-layer architectures with parallel waveguides and electrodes, the following objectives are of interest

- Number of layers
- Number of stages
- Implementation issues.

where the number of layers and NS are dependent, i.e. if the number of layers decreases, NS increases (Table 3). Additionally, the range of possible architectures is very much restricted by the implementation (e.g. switching between embedded N-gon prisms by means of electrodes at the outer and inner prism and no new electrode). First of all, we have to chooce the technology/concept (a) to (c) (Sub-Section 3.5) and route signals from the inputs to the permuters and from them to the outputs. Throughout the paper, we discussed expanders and concentrators based on multilayer-architectures according to (c). However, cases (a) and (b) may also be applied. Note, the planar realization of the switches resolves the implementation difficulties.

There exist construction principles of expanders and concentrators where double covers and the second large eigenvalue comes in [27,28]. However, the crucial problem is their all-optical implementation rather than to obtain a large expansion/concentration coefficient and small number of edges. Once we have constructed efficient expanders and concentrators in this way, we may not be able to implement them optically in a spatial manner, except by the resolution of the

interconnections via several stages. But in this case, we leave the $O(1)$-switch principle, i.e. NS will depend on the number of inputs/outputs.

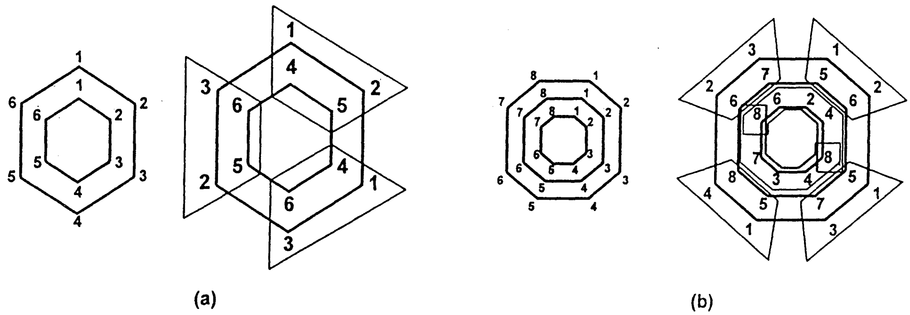


Fig. 14. Organization of the shells of the proposed optical switch. Intersection of the expanders/concentrators at the lhs and numbering of the parallel permuters/destination routing at the rhs. (a) 6×6-switch. (b) 8×8-switch where the inner 4-permuters switch between 2 and 4, 2 and 6, 4 and 8, 6 and 8 (upper switch 2, 4, 6 and 8) and between 3 and 4, 3 and 7, 4 and 8 and 7 and 8 (lower switch 3, 4, 7 and 8).

These problems are solvable by graph topology (coverings, liftings), group theory and combinatorics. For example, Fig. 14 shows, in principle, a covering solution though it was obtained by coset decompositions of permutations (and, in the limit, by the decomposition into 2-cycles) [19]. There exist several nonisomorphic coverings, some of them are countable [29,30], though, in general, their computation is NP-complete [31]. Additionally, we may wish to increase the number of connections between the embedded prisms [32,33], in order to further reduce NS or implement expanders/concentrators. Such an attempts is similar to the multidimensional case in [22], though the implementation of the required 2×2-switches may be difficult.

5. Conclusions

The extension of common planar all-optical switching principles into the 3-D physical space provides novel all-optical switching architectures. The advantages are the least number of 2×2-switches and the least number of stages for rearrangeable nonblocking interconnections and for the capability to operate in the circuit switching mode. Additionally, the dynamics of the switches (difference of path lengths) is expected to be a minimum. With an extension of the architecture to the embedding of several prism switches and the increase of the connectivity between the prisms, the number of stages may be further reduced. The same principle may be applied to construct all-optical expanders and concentrators. These components may also be applied to implement optically the shells at the lhs and rhs of the parallel permuters which route data from the inputs to the parallel permuters and from the permuters to the outputs. However, the spatial optical implementation may cause considerable difficulties. Therefore, the equivalent planar counterparts have been presented for the simplest case though more complicated architectures may be designed in a planar way according to the principles in Sub-Section 3.3.

Acknowledgement

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Crosstalk in WDM optical networks

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Abstract
The impact of linear and non linear crosstalk on the transmission performances of multi-wavelength optical transport networks is analysed. A performance evaluation of some relevant geographical networks is also reported.

I-INTRODUCTION

The transmission capacity and the network nodes throughput are expected to increase more and more, due to the increasing demand for new services, towards the advent of broadband communications. The optical technology provides the possibility of significantly increase the transmission capacity and, by the use of wavelength division multiplexing technique, also allows switching and routing functions to be accomplished directly in the optical domain, without the need to convert the high speed signals in electrical format. The possibility of achieving such function quite independently of the transmission format and the signal speed, provide the network the property of transparency, which is a significant feature for building flexible networks.

Different demonstrators and field trials have been realised [1,2]. In such experiments, it has been evidenced that the crosstalk, besides the node losses and the amplified spontaneous emission (ASE) noise due to optical amplifiers, represents the main limitation for the transmission performance of the network.

The aim of this work is to analyse the limitations imposed by crosstalk to the performances of the WDM optical transport network layer.

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II-CROSSTALK ANALYSIS

Basically, it is possible to distinguish two types of crosstalk, depending on the nature of the effects that generate it: linear and non-linear crosstalk. Linear crosstalk originates in the optical cross-connecting node (OXC), while non-linear crosstalk arises from four-wave mixing in fibre (FWMF), which is generated in high speed-long distance WDM transmissions.

Linear crosstalk can be further categorised in two categories: hetero-wavelength crosstalk (HEC) and homo-wavelength crosstalk (HOC).

Hetero-wavelength crosstalk. This effect is generated by the spectra tails of the adjacent channels entering the bandwidth of the selected channel, and by non-ideal filtering (the filter transfer function is not rectangular). In a real network the spectrum of the channel is distorted by the transit through the OXC's due to the presence of non ideal filters. In particular, the spectra tails are attenuated and the total crosstalk contribution depends on the path followed by the interfering channels through the network. Moreover, it depends on the relative polarisation of the channels, on the relative phase of the optical carriers and on the relative phase of messages transmitted on different channels.

Considering that it is not possible to take rigorously into account all these elements, in the analysis we consider a worst case approach. It is assumed that the spectra of the interfering channels are not altered in the transit through the OXC before the crosstalk generation itself. As a matter of fact, crosstalk can be described as a random process generated by the sum of many independent contributions. This process can be regarded as an additive Gaussian noise, since the polarisations and the phases of the optical channels are uncorrelated each other. It is worth observing that if the overall optical bandwidth is roughly comparable with the bit rate, such a noise can be schematised as white noise. Its noise power can be expressed analytically as:

$$\sigma^2 = \int_{-\infty}^{+\infty} \left|H_s(\omega)\right|^2 \cdot \sum_{k=1}^{N} \left|H_x(\omega)\right|^{2(N+1-k)} \sum_{j=1, j\neq y}^{M} S(\omega + jd\omega)\, d\omega \quad (1)$$

where the selected channel is indicated with y, while $H_X(\omega)$ and $H_S(\omega)$ represent, respectively, the transfer function of the OXC and of the selection filter at the receiver. $S(\omega)$ is the power spectral density of one of the transmitted channels, N is the number of fiber links and M represent the number of channels belonging to the comb.

Homo-wavelength crosstalk. Homo wavelength crosstalk happens when a channel interferes at the OXC output with crosstalk components at the same wavelength. Such crosstalk contributions, that accumulate coherently along the

transmission path, can be originated either by adjacent channels, and by the same channel that traversed the OXC along a spurious path: in particular they are generated every time the channels are WDM multiplexed by a passive combiner, as is shown in fig.1. The devices that generates HOC contributions are either optical filters and switch matrixes.

In fact, due to the non ideal filtering of the optical filters inside the OXC, and the imperfect behaviour of the switching matrices, spurious contributions, from other channels carried by the same wavelength of the considered channel, sum at the combiners (placed either at the OXC and at the matrix output). Such contributions can be regarded as in-band crosstalk and propagate together with the channel. Since this effect occurs in each OXC, this kind of crosstalk accumulate and cannot be eliminated. HOC generated by other channels at the same wavelength can be modelled similarly as the HEC. So it is possible to consider it as a noise and derive its noise power adopting the same model used for HEC. In particular equation (1) holds with $\Delta\omega=0$.

On the other hand, HOC originating from the replica of the same channels through different optical paths inside the OXC (self-interference), can't be modelled as a noise, due to its coherent nature. However this kind of HOC can be drastically reduced if wavelength conversion is adopted inside the OXC [3].

Moreover, HOC originating from self-interference can be considered uncorrelated with the signal itself and modelled as a noise, if it is assumed that the optical path between the demultiplexer and the optical combiner is longer than the length of coherence of the transmitters. This hypothesis is always verified if not all the OXC's devices are monolithically integrated.

Non-linear crosstalk. Non linear crosstalk is due to Four Wave Mixing arising during fibre propagation for the presence of Kerr non linearity. In order to schematise this crosstalk contribution, we adopt the same approach used for linear terms. In particular, FWMF spectral power density contributions are calculated as described in [3,5] where the validity of the Gaussian approximation is also discussed. It is worth noting that the non-linear crosstalk terms accumulate incoherently, since the channels at the same wavelength changes throughout the network.

Since any crosstalk contribution can be regarded as white Gaussian noise, the total crosstalk power can be evaluated by summing the different noise powers.

III-SIMULATION MODEL

To evaluate the transmission performances of the network, we consider a generic signal path through the network consisting in: an originating OXC, containing the transmitter, a chain of in-line OXC and a final OXC that contains the receiver. The transmitter is supposed to be composed by a single mode laser externally modulated by a Mach -Zender modulator. The receiver is constituted by a p-i-n diode, a Gaussian electric filter and a decision circuit. Optical amplifiers

(EDFA) are present in the fiber links in order to compensate for fiber losses. Different node architectures have been proposed in literature: here we consider the one proposed and realised in the RACE-MWTN project [1] and reported in fig.2. The realised simulator can evaluate the transmission performances (in terms of bit error rate) of a generic optical path through the transport network. It numerically simulates the evaluation of the signal up to the decision circuit of the receiver. Then the exact error probability is calculated applying the characteristic function method and the "Saddle Point Approximation"[3]. Besides all the distortion contributions, the obtained error probability takes into account the optical noise due to the accumulation of amplified spontaneous emission (ASE) of the optical amplifiers, the thermal noise and the crosstalk contributions.

The signal propagation in the fiber is simulated considering attenuation, chromatic dispersion, and Kerr effect (in particular self-phase modulation). In the numerical simulation of the signal through the network, the modelling of the crossed optical devices is taking into account, by their transfer functions or by theri phisycal modelling, according to the complexity of their behaviour.

Moreover, we develop a model that into account the matrix internal crosstalk and the ASE power generated by the semiconductor optical amplifier (SOA) used ad switching elements [6].

The overall error probability is evaluated by averaging the BER calculated for each bit of a random signal pattern, whose length is long enough to take into account memory effects of the transmission system, mainly due to chirping/dispersion.

IV-RESULTS AND DISCUSSION

In order to test our simulator we referred to a real network (SGN: Stockholm Gigabit Network) [7], realised in the framework of the RACE-MWTN project. In fact, our simulation results were compared with the experimental measures achieved on such a network. The OXC architecture is reported in fig.2. The channels discrimination is achieved by means of optical power splitters and tunable filters (double stage acousto-optic filters). The space switching is realised through optical switching matrices based on InP technology, and using optical amplifiers as switching elements. The OXC has four input fibres, each carrying a comb of four WDM channel. The transmission performances relating to 2.5 Gb/s channels, obtained either by simulation or by measures, are reported in fig. 3. The agreement between experimental and simulated results can be considered quite satisfactory.

To analyse the crosstalk effect in optical networks covering much wider geographic areas we considered, as an example, a possible Italian optical transport network. In particular we referred to a transmission path 1650 km long.

As far as 10 Gb/s systems is concerned, we accoplished several simulations in order to evaluate how non ideal optical filtering, inside the OXC's, influences the transmission performances. In particular we consider the following types of optical filters:

- single and double stage Fabry-Perot filter,
- single and double stage acousto-optic filter,
- apodized acousto-optic filter,
- interference filter.

The OXC is supposed to have four input fibres each carrying a comb of four WDM channels, 4 nm spaced. The optical filter one side bandwidth is 200 GHz, while the optical selection filter and the receiver electric filter bandwidths are respectively 2R and R (R=10 Gb/s). Moreover the selection filter in front of the receiver is assumed to be single Fabry Perot. The main parameters adopted in the simulations are reported in table 1. The fibre links are realised by a dispersion shifted fibre with dispersion coefficient D=4 ps/nm/km and an attenuation of 0.25 dB/km. In line EDFAs are 50 km spaced and, after each EDFA, a dispersion compensating fiber is placed.

As it is shown in fig.4, neither the use of Fabry Perot filters nor the use of single stage acousto optic filters, allow satisfactory transmission performances to be achieved. On the other hand, if channel spacing is large enough, as in the considered case, double stage acousto optic filters and apodized acousto optic filters assure good performances. In particular a suppression of the side lobes from -9 dB to -15 dB is achieved, using apodized acousto optic filters instead of simple double stage ones.

Optimum results can be obtained using interference filter. This kind of filters is characterised by a flat transfer function and by the absence of side lobes; however there are not yet tunable filter available. Their use inside the optical cross connects reduces the flexibility of the network. In table 2 we report the signal to homowavelength contribute ratio obtained with different kind of filters.

In the crosstalk analysis we also consider high density WDM systems (8 channels per fibre, 1.5 nm spaced). In this case, the optical filter onr side bandwidth inside the OXC is 130 GHz.

The simulation results are reported in fig.5. It is worth noting that, also in this kind of systems, the best performances are achieved if interference filters are used. In table 3 we report either the signal to homowavelength contribute ratio and the signal to heterowavelength contribute ratio, that become significant for the selected value of $\Delta\lambda$.

V-CONCLUSIONS

Linear crosstalk, and in particular homo-wavelength crosstalk, imposes significant limitations to the performances of WDM optical transport networks. This limitation can drastically reduce if highly selective filters (high roll-off factor), and switch elements with high ON/OFF ratio are utilised in the cross connect. Non linear crosstalk, due to Four Wave Mixing in Fibre is not significant if national

transport network is analysed. However it become determinant if international geographic link (beyond 2000 km) is considered.

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Transmitter extinction ratio	20 dB
Receiver sensitivity	-29 dBm
Optical amplifier noise factor	2.6

Table 1. System Parameters

TYPE OF FILTER	SNR-HOC (dB)
Single stage F-P	9.31
Double stage F-P	12.32
Single stage A-O	17.23
Double stage A-O	24.14
Apodized double stage A.O	27.59
Interference Filters	33.09

Table 2: Signal to HOC contribution ratio (SNR-HOC) for different kind of optical filter: 4 channels per fibre 4 nm spaced.

TYPE OF FILTER	SNR-HOC (dB)	SNR-HEC (dB)
Double stage A-O	21.14	26.23
Apodiz. double stage A-O	23.21	26.21
Interference	30.75	26.11

Table 3: Signal to HOC contribution ratio (SNR-HOC) and signal to HEC contribution ratio (SNR-HEC) for different kind of optical filter: 8 channels per fibre 1.5 nm spaced.

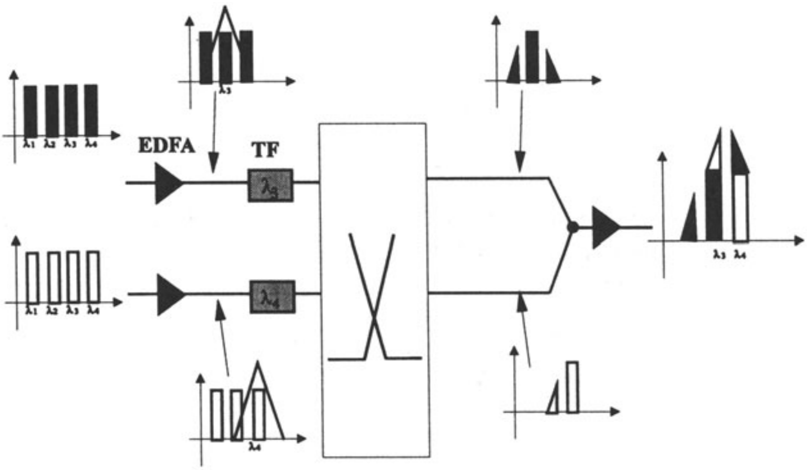

Figure 1. Homowavelength contribution generated in the channel selection.

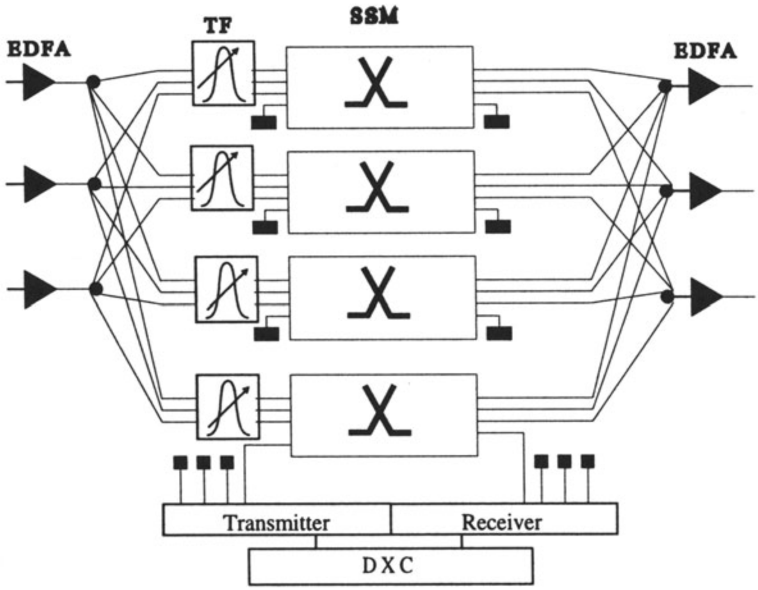

Figure 2. Block scheme of the optical cross-connect. EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; SSM: Space Switch Matrix; DXC: Digital Cross Connect.

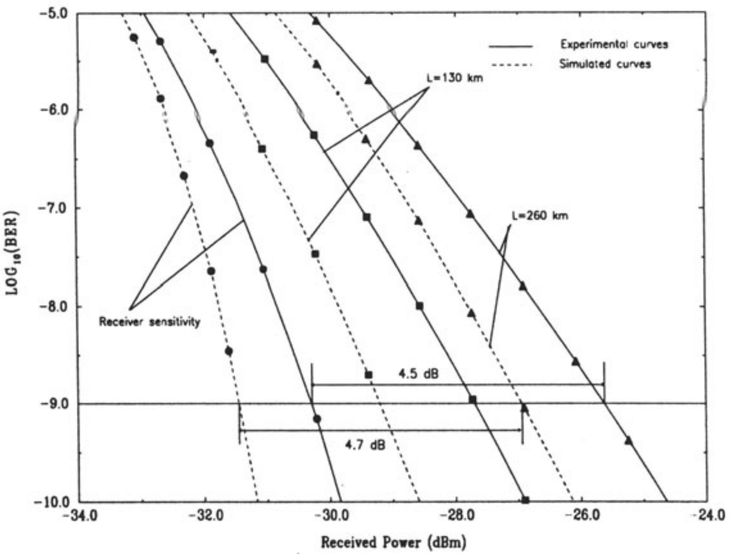

Figure 3. Transmission performances, regarding the Stockholm Gigabit Network, obtained experimentally and with the simulator.

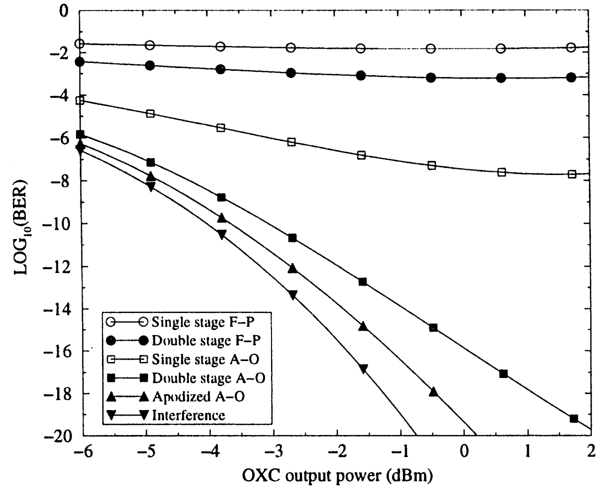

Figure 4. Transmission performances of low density WDM systems (4 channels 4 nm spaced) with different kind of optical filters.

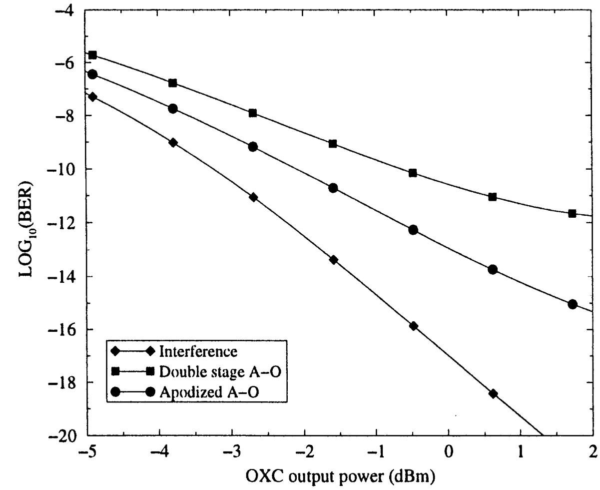

Figure 5. Transmission performances of high density WDM systems (8 channels 1.5 nm spaced) with different kind of optical filters.

Photonic Network Design Based on Reference Circuits

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Abstract

The ever increasing demand for network capacity is driving new technologies into realization. One of these are future transparent Photonic Networks, providing considerably more functions than plain transmission only through independent routing of signals by means of Wavelength Division Multiplexing. However, the analogue nature of such Photonic Networks results in an accumulating degradation of the transported optical signals and prevents the application of simple design rules.

The objectives of this presentation are to clarify specific terms like transparency and transverse compatibility, and then to derive guidelines as a first approach to an engineered Photonic Network. These guidelines are applied to the planning of a core network with 8 and 16 wavelength channels per link and verified by first numerical results.

Complementary to a layered network architecture, our methodology is based on the use of a specific reference configuration. Degradation effects like amplifier noise, chromatic and polarization-mode dispersion, non-linear self phase modulation are covered as well as node crosstalk and the impact of optical frequency misalignments. Based on ITU-T recommendations, a classification of ranges of bitrates and other preliminary specifications, our method allows to assemble a general Photonic Network from its elements in a bottom-up scheme.

As a result, we show that Photonic Networks could exhibit transparent optical paths, ranging from 400 to several thousands of kilometres. A number of 16 wavelength channels at individual bitrates of up to 10 Gbit/s traversing a couple of crossconnecting nodes can be implemented, taking into account present-day optical components like amplifiers, standard fibres, multiplexers and demultiplexers, fibre switches as well as dispersion compensating techniques. The potential benefits of such networks are to be seen in their inherent high capacity and in a high degree of flexibility, supporting various applications.

Considering the results obtained so far, it can be concluded that a country of the size of Germany could be covered by a transparent Photonic Network.

1. Introduction

Fibre networks with considerably more functions than plain transmission are called Photonic Networks. Wavelength Division Multiplexing (WDM) is one of the features of such networks for multiplexing and optical routing of independent signals. This makes it possible to form an "underlying" network which supports other networks. The achievable transparency, high capacity, good transmission quality and robustness make Photonic Networks attractive. Insofar, many field trials are under way around the world.

However, a fundamental problem of Photonic Networks results from its analogue nature.

The transported optical signals suffer from continuous and accumulating degradation on their way through the fibre network. This degradation is not yet well known in all details and prevents the application of simple design rules for such networks.

This contribution is a first step to develop guidelines for realising Photonic Networks. Accompanying quantitative calculations indicate that this approach seems to be principally reasonable.

Optical Network Design and Modelling H. van As & A. Jukan (Eds.)

2. Photonic Networks and the Role of WDM

A Photonic Network is here understood as a network

- which consists of interconnecting lines and network nodes
- which is suitable for optical transmission with high capacity
- which is based on widespread use of WDM
- which allows initial configuration, later reconfiguration due to changing traffic demands, and restoration in case of line failures
- which provides maximal transparency for present-day and future services and signal types, including "leased lines" with parameters still to be defined
- which processes the signals in the optical domain
- which is based on the joint use of space and frequency switching
- which has integrated supervision and management facilities with technical standards comparable to those of SDH equipment
- which provides "embedded" transport of OAM information within the network
- which is compatible with existing transmission equipment regarding
  - optical interfaces
  - switching times and
  - network management.

In short, a Photonic Network is a sophisticated and switchable replacement of an optical fibre plant.

2.1. Analogue Character and Reference Configuration

In digital networks no substantial signal degradation occurs during transmission and within the equipment. It is therefore sufficient to describe it by means of the "layered network architecture" and by "functions" in every layer.

On the other hand, and seen from many aspects like

- power levels
- dispersion
- frequency distortion
- noise accumulation and
- crosstalk

the Photonic Network has clearly features of an analogue network. Quasi-analogue transmission leads to an accumulating degradation, even if all components work as assumed.

The layered network approach is therefore less suitable and not sufficient to describe the analogue effects.

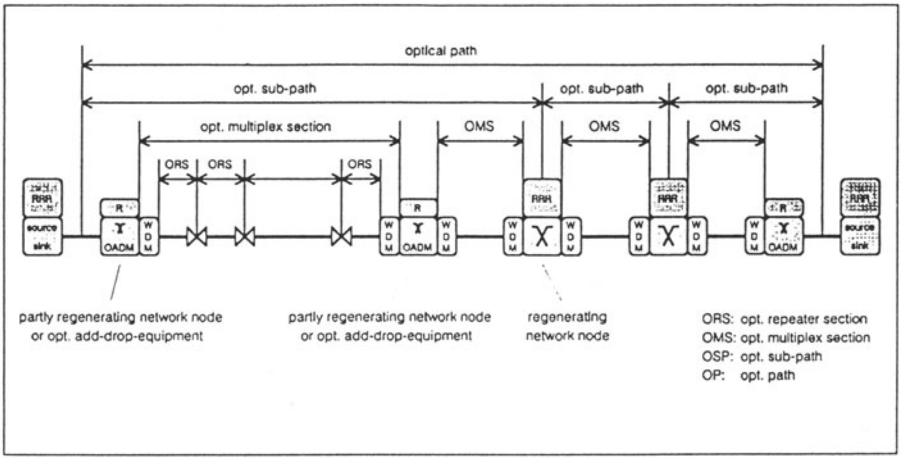


Fig. 1: Photonic Network Reference Circuit

In addition, a reference configuration is proposed, with

- partly regenerating optical crossconnects
- optical add/drop multiplexers
- fully regenerating crossconnects
- nonregenerating repeaters or amplifiers, and with
- optical source and sink, which are normally outside the network.

This reference configuration defines

- an "optical wavelength path" which goes from the source to the sink reference points
- "optical subpaths", terminated by fully regenerating crossconnects
- "optical multiplex sections", ranging from crossconnect to crossconnect or optical add-drop-multiplexer, and
- "optical repeater sections" between nonregenerative repeaters.

The transparent optical sub-path consists of cascaded optical repeater sections and multiplex sections. Cascading of several sub-paths is not critical due to the complete regeneration at the end of each sub-path.

The basic parameters for a first calculation of an optical repeater section are summarised in Table 1.

bitrate class		class 1	class 2	class 3
maximum bitrate	(Gbit/s)	0.7	2.5	10
application	SDH SONET PDH	up to STM-4 up to OC-12 34/140/565 Mbit/s	up to STM-16 up to OC-48	up to STM-64 up to OC-192
standard fibre acc. ITU-T G.652		yes	yes	yes, plus dispersion compensation
target distances (ORS length)		120 km	120 km	80 km
ORS attenuation (0.275 dB/km)		33 dB	33dB	22 dB
EDFA noise figure (assumed)		5 dB	5 dB	5 dB
maximum launched power, total		+ 17 dBm	+ 17 dBm	+ 17 dBm
per channel (8 channels)		+ 8 dBm	+ 8 dBm	+ 8 dBm
per channel (16 channels)		+ 5 dBm	+ 5 dBm	+ 5 dBm

Table 1: Basic Reference Circuit Parameters

2.2. Network Evolution

The final goal to implement a Photonic Network may be reached by evolutionary introduction of WDM to existing fibre networks in several steps:

- in a first step, for capacity enlargement in point-to-point links
- in a second step, for flexibility and protection in WDM rings
- in a final step, as a general means to enlarge capacity and flexibility of the network.

The first form of application leads to rather simple WDM equipment, the second and the third lead to much more stringent requirements, as regards frequency stability, optical frequency and dispersion equalization, power level management, and crosstalk.

2.3. Transparency

The original idea of transparency was to have a network into which one could launch any optical signal and nothing in the network would interfere with its transmission, and only the terminal equipment would determine the limitations of the signal.

At a closer look we can see that there are limits to almost every parameter of the signal. Many of those limits depend on its physical properties and so full transparency cannot be achieved.

A Photonic Network should provide transparency for all types of signals up to a feasible upper limit according to the state of the art, i.e. up to the order of 10 Gbit/s.

The demand for transparency is to be limited regarding several aspects:

- the characteristics of the signals to be transmitted
- fibre nonlinearities and power levels
- crosstalk in wavelength selective components and switches
- the maximum length of regenerator and multiplex sections
- the accumulated noise and hence the signal-to-noise-ratio (which depends on the bit rate)
- the physical properties of the fibre like frequency-dependent attenuation and dispersion compensation
- the need to specify standard wavelengths of the system in order to guarantee interworking.

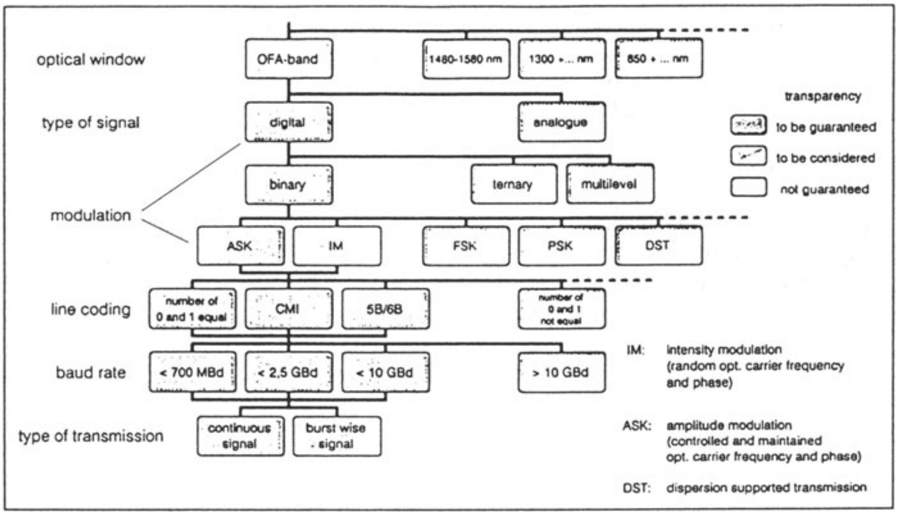


Fig. 2: Transmission Procedures and Transparency

Our definition of transparency is largely in line with an already known proposal:

- optical window is the OFA band
- the type of signal to be transported is digital
- binary modulation is assumed
- the modulation formats are ASK, and IM,
- statistically scrambled signals and CMI or 5B/6B coded signal are transmitted
- line baud rate is up to 10 Gbit/s
- continuous signals are transported, burstwise signals are excluded on account of potential difficulties
- optical frequencies and their stability are to be considered.

The shaded issues are essential and must be met. Other types of signals may also be transported, but this is not essential. Note that analogue signals like TV are explicitly excluded.

The finally agreed degree of transparency should be clarified very early, because it influences many parameters.

Due to economical reasons, it seems not the best way to make every link suitable for signals up to the highest bitrate. Achievable link lengths, number of cascadable amplifiers, receiver sensitivity, and so on, depend on the maximum bitrate. It is therefore advisable to distinguish between several "classes" of links.

2.4. Bit Rate Classification

We take the channel bandwidth as the basis for a bit rate classification:

- class 1, which is suitable for signals up to 700 Mbit/s per channel

-class 2, suitable for signals up to 2.5 Gbit/s per channel

-class 3, for signals up to 10 Gbit/s per channel.

Higher classes should also be usable for transmission of signals of lower classes. It is however to be studied if "downgrading" imposes higher requirements on the equipment.

2.5. Potential Frequency Allocation

Frequency allocations for WDM systems should

- provide as much commonality as feasible
- take state-of-the-art amplifier, transmitter and filter parameters into account
- be based on existing systems and frequency allocations

and

- leave a certain freedom for individual realizations and technical progress.

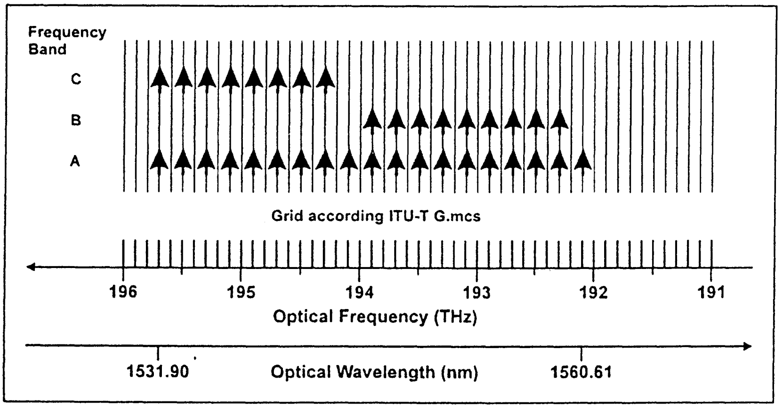


Fig. 3: Wavelength / Frequency Channel Allocation

This proposal is based on a 100 GHz grid within the 1550 nm band, with the grid "anchored" at 193.1 THz. In view of optical amplifiers and filters, use of band A with 200 GHz spacing of channels is foreseen. Preferred subbands are B (with 9 channels), and C (with 8 channels). Even spacing of channels is assumed for use with standard single-mode fibres. Uneven spacing must be mainly used with fibres according to G.653.

2.6. Dominant Penalty Principle

For our calculations we use the "dominant penalty" principle. All degradation effects for cascaded link elements and nodes are treated separately. The "1 dB power penalty" criterion is used for each single effect, and the maximum number of cascaded elements is calculated. The dominant degradation effect is determined by the smallest number of cascadable elements. This is taken as the upper limit for the whole system. By lowering the dominant effect, the whole system could be improved.

In the next steps, these principles are applied to the links and to the nodes. The result is an estimation of the network size and capacity which could be built on the basis of the possible number of cascaded units.

The last step is an evaluation of the achieved path performance, considering all remaining effects which are not included in the preceding procedure.

2.7. Link Dimensioning

The maximum length of a transparent sub-path is limited by different degradation effects. Strong degradation effects lead to short sub-path lengths.

A common approach is to obtain the longest possible transparent sub-path length by optimising all link parameters. Our approach is cascading identical sections with given target distances, which are in line with ITU-T practice, as shown in the reference configuration. The drawback is of course that we do not necessarily obtain the longest possible sub-path lengths. However, benefits are:

- a simplified link design by cascading identical repeater sections
- separation of degradation effects by treating all degradations separately with the "1-dB-penalty" criterion and then applying the simple "dominant penalty" principle
- obtaining a single parameter, the number of maximum cascadable sections
- getting a certain degree of modularity.

2.8. Link Degradation Effects

A sub-path suffers mainly from the following degradation effects of accumulating character:

- amplifier noise
- polarization mode dispersion
- chromatic dispersion
- non-linear self phase modulation (SPM) in combination with chromatic dispersion

The amplifier noise contribution e.g. can be calculated by means of the formulas given in a recent draft of an ITU-recommendation.

Measurements on installed fibres give actual PMD values. PMD sets hard limits for the maximum transmissible bitrate; this justifies again the bitrate classification.

The non-linear SPM is a fibre effect which depends on the actual optical power and bitrate, resulting in a broadening of the optical spectrum. A broader spectrum suffers more from chromatic dispersion, therefore the combined effect of SPM and chromatic dispersion has to be considered.

Other non-linear effects like

- stimulated Brillouin scattering
- stimulated Raman scattering
- cross-phase modulation
- four-wave mixing

have been calculated to be negligible on standard fibres with power levels below + 15 dBm.

Basic Transmission System Parameters:

Bitrate class	class 1		class 2		class 3	
Maximum bitrate	0.7 Gbit/s		2.5 Gbit/s		10 Gbit/s	
Target ORS-distance	120 km		120 km		80 km	
Number of wavelength channels	8	16	8	16	8	16
ORS launched power per channel	+8 dBm	+5 dBm	+8 dBm	+5 dBm	+8 dBm	+5 dBm

Maximum Number of Repeater-Sections (ORS) due to Individual Limiting Effects:

Amplifier noise accumulation	44	22	12	6	39	19
Combined self-phase modulation and dispersion	3476	6934	221	439	16	32
Polarization mode dispersion (0.1 ps/sqrt(km))	21300	21300	1333	1333	125	125
Polarization mode dispersion (0.5 ps/sqrt(km))	853	853	53	53	5	5
Four Wave Mixing	125	400	125	400	125	400

Table 2: Maximum Number of Optical Repeater Sections

Table 2 shows the number of achievable repeater sections as a result of the first calculations.

The shaded numbers indicate the dominant degradation effect. From these, the maximum length of sub-paths is easily obtained.

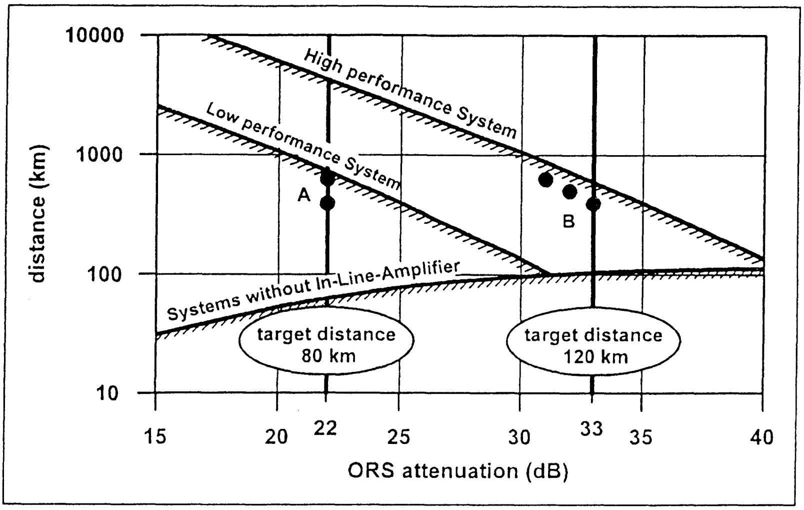


Fig. 4: Achievable Sub-Path Length as a Function of the Repeater Section Attenuation

The boundaries mark systems without in-line amplifiers, and systems with in-line amplifiers of low and high performance.

The following can be concluded:

- the range of sub-path length varies up to one decade between systems with amplifiers of low and high performance
- reducing the ORS span length or attenuation (i.e. the target distance) improves the achievable total distance.

It is however to be considered to stick to ITU-values.

3. Network Node

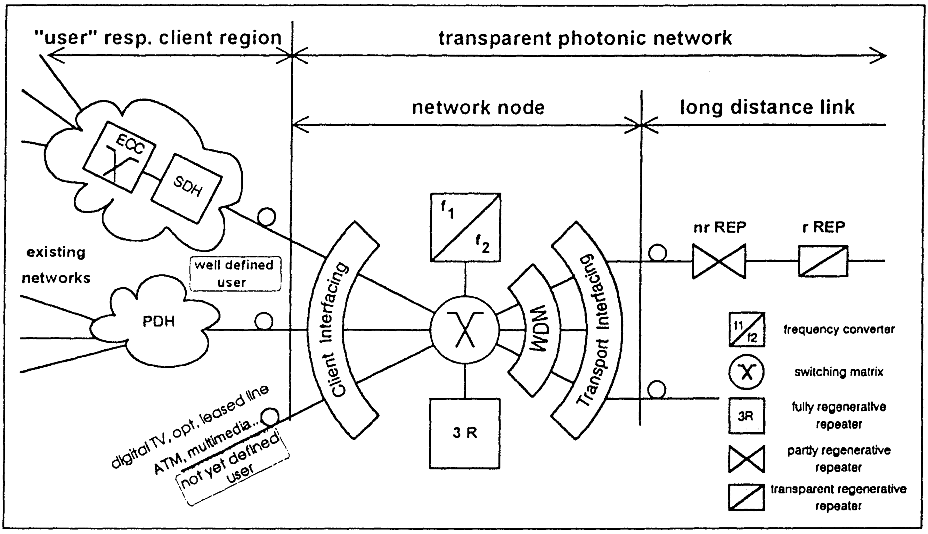


Fig. 5: Network Node

A network node consists principally of a switching matrix which is "shielded" against the environment by interfacing circuits, working together with 3R-regenerators and frequency converters as required. A distinction could be made between

- transport nodes with transport interfaces, which are located within the switchable network, and
- access nodes, which provide client interfaces for access to the network.

In practice, every real node will be a mixture of both, because normally network nodes will be at locations where access is also necessary.

3.1. Node Performance

The maximum number of cascadable repeater sections in an optical sub-path has been evaluated. Now we replace optical amplifiers by transparent non-regenerating nodes. Each node is considered to be equivalent to one amplifier in view of degradation effects like noise accumulation. This substitution then causes no changes in the sub-path noise performance. The insertion loss can be easily compensated by additional amplifiers, as long as their noise contribution is negligible.

Crosstalk, however, can cause serious problems.

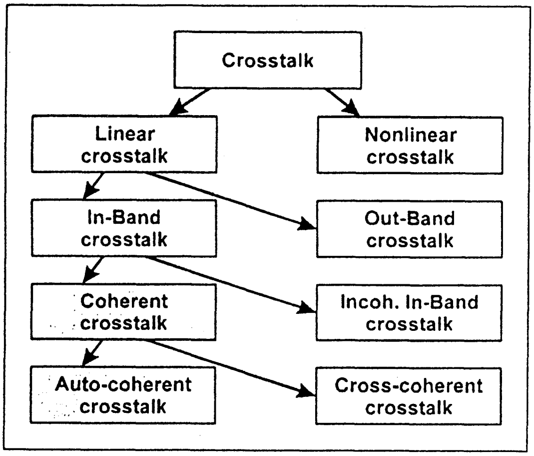


Fig. 6: Crosstalk in WDM Networks

The strongest crosstalk contribution is the "coherent crosstalk". Different optical signals with identical nominal frequencies interfere within the receiver bandwidth (this is the "cross-coherent crosstalk"). A signal which interferes with itself by multipath propagation causes "auto-coherent crosstalk".

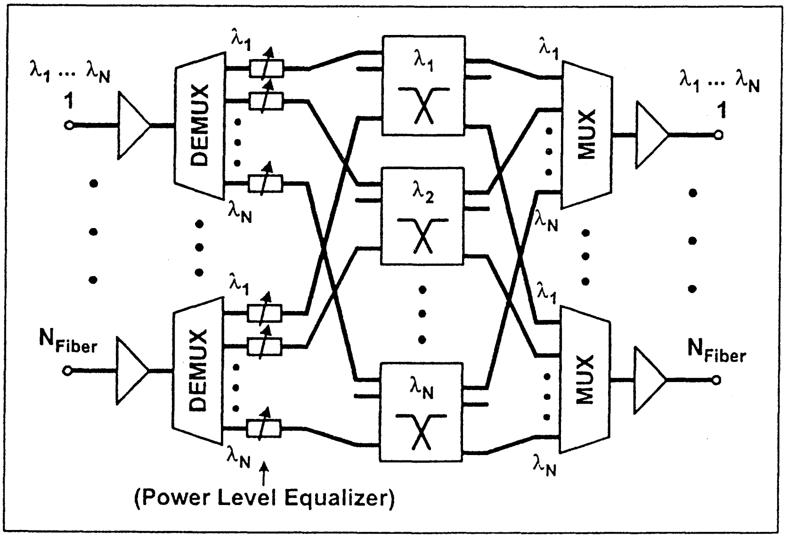


Fig. 7: Wavelength Path Crossconnect

In a simple switching node all wavelength channels from the incoming fibres are first demultiplexed and then switched to the output fibres. This type of node may suffer from a higher degree of blocking probability.

With such nodes the "Wavelength Path" concept can be realised. A better performance may be obtained using the "Virtual Wavelength Path" concept with optical frequency converters within the nodes. Such a node is much more complicated and it is not yet confirmed that the Virtual Wavelength Path concept is superior to the simpler Wavelength Path concept.

The procedure of evaluating the coherent crosstalk is to figure out all possible spurious paths within the node and then to compare the summation of the spurious signals with the power level of the main path. All demultiplexers, switches and multiplexers contribute to the resulting crosstalk. Finally, the 1 dB-penalty level of crosstalk is obtained by the analysis published by Takahashi.

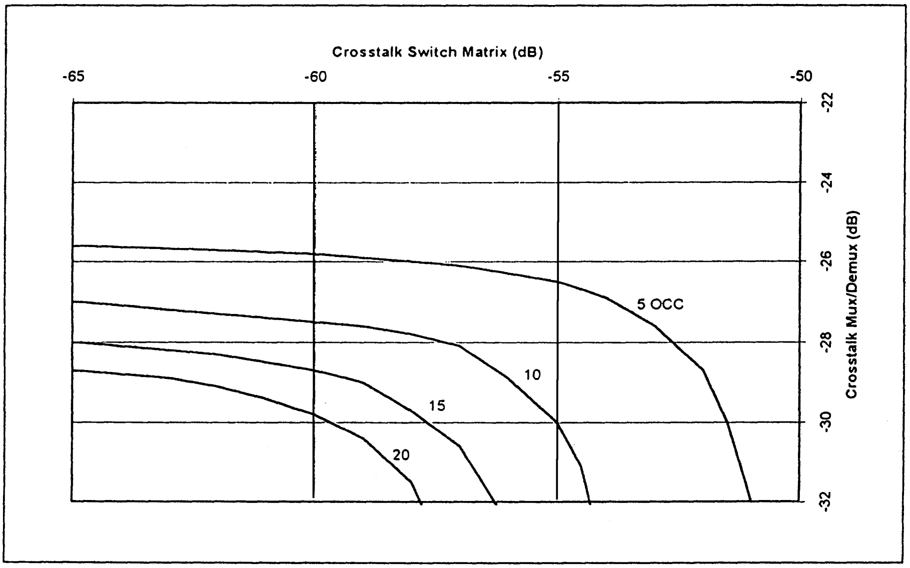


Fig. 8:Tolerable Crosstalk in Crossconnects

Fig. 8 shows the results for a number of cascaded nodes.

The area below the curves shows the region where the power penalty is below 1 dB.

A certain trade-off is possible between the performance of the multiplexers and demultiplexers and the switch-matrices. If space switches with excellent crosstalk performance (of the order of 60 dB or better) are used, each multiplexer may have down to 27 dB crosstalk attenuation. If the space stage has a crosstalk attenuation worse than 52 dB, the configuration becomes unsuitable even with excellent multiplexer and demultiplexer performance.

The calculated crosstalk requirements seem realistic. Commercially available multiplexers and demultiplexers exhibit crosstalk levels down to - 30 dB, and crosstalk levels of a matrix based on fibre switches may well be below - 60 dB.

3.2. Interfaces

3.2.1. Client Interfaces

Interfaces for users are provided at specific ports of network nodes. Users may be either single pieces of equipment, like SDH or PDH equipment, or whole networks. All client interfaces should accept all signals within the limits discussed.

Two different approaches are feasible:

- interfaces are generally usable, i.e. transparent within the constraints shown, or
- interfaces are specialised, e.g. for SDH of specified bitrate.

If unavoidable, "noncompliant" client signals could be made compliant via specific "adapters". Those compliant transmitters would then be part of the network.

Client interfaces should provide some precautions against erroneous input signals, as regards amplitude and frequency, to avoid disturbances of other signals in the network.

3.2.2. Transport Interfaces

Network-side or transport interfaces must be transparently adapted to the parameters of the transmission medium. Their task is

- to provide and accept the appropriate power levels, and
- to care for amplitude and dispersion equalization of the link

4. Open Issues

A couple of additional problems have to be solved prior to network implementations.

4.1. Filter Cascading

The stability of optical frequencies has a major impact on network design.

An optical sub-path has to traverse several multiplexer and demultiplexer stages. Since the passbands of these filters are not perfectly flat, their cascading leads to an increasing passband narrowing. This is investigated in the simple add/drop ring network shown here.

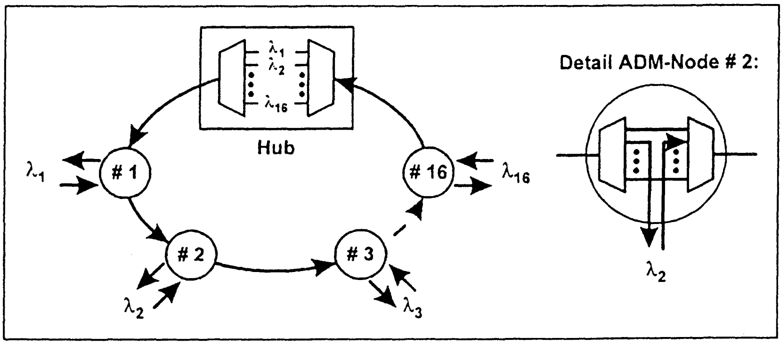


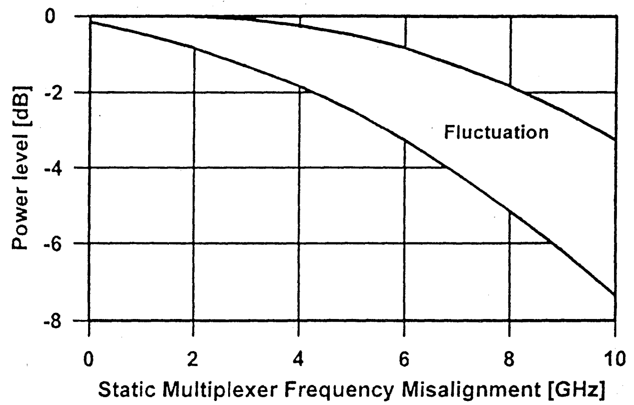
Fig. 9: WDM-Ring with 16 ADM-Nodes

Arrayed waveguide gratings as multiplexers and demultiplexers have a nearly Gaussian passband characteristic. The resulting bandwidth is reduced with the square-root of the number of devices in cascade. In the example shown, the maximum number of cascaded devices equals 32.

wavelength channel spacing	200GHz
1 dB bandwidth of each multiplexer/demultiplexer	50 GHz
1 dB bandwidth of a 32-device cascade	8.8 GHz
suitable for maximum bit rate class	class 2; 2.5 Gbit/s

Table 3: WDM-Ring Performance

In addition to the bandwidth narrowing effect, a second influence can lead to path degradation. If all centre frequencies are not perfectly aligned and if additional short-time fluctuations of the centre frequencies (due to temperature changes, change of polarization states etc.) cannot be excluded, the received optical power fluctuates as shown.



(calculated for dynamic frequency deviation of AWG-filters: ± 2 GHz)

Fig. 10: Power Level Fluctuations in a 16-node ADM-Ring

A short-term fluctuation of 2 GHz for each device is assumed. In order to keep the resulting power fluctuations below 1 dB, the static centre frequencies should be aligned to better than 2 GHz. The requirements on the frequency accuracy of each laser transmitter are of the same order.

Cascading of filters has a strong impact on path performance.

Therefore

- a flat passband characteristic for multiplexers and demultiplexers is mandatory
- a flat passband may be obtained at the expense of additional insertion loss; this should be acceptable within certain limits.

The impact of filter characteristics and slopes on dispersion has not yet been considered.

4.1.1. Frequency Referencing

For reasons already considered it may be necessary to consider frequency referencing techniques. Possible implementations are

- stabilization by local references or
- locking to distributed absolute reference frequencies within the network.

4.2. Power level control

Measures have to be developed to keep the power level at each interface point within specified ranges. The static as well as the dynamic behaviour of power levels ("optical transients") of switched optical paths is an important issue and must be considered.

4.3. Monitoring of Optical Path Performance

Monitoring must be an integral part of the network. Quality performance of active and standby channels must be known and guaranteed for the relevant class. Furthermore, degradation effects should be distinguished and localised.

4.4. Network Management in Transparent Systems

Transport systems, such as SDH, have well defined internal means for dealing with faults and performance monitoring, and whatever is done in the optical network must work together with the transport systems. If there is a fault, both the SDH layer and the optical layer will know about it and means must be implemented to co-ordinate their response.

As different transport systems (like SDH and FDDI) may share the same transparent Photonic Network, the network management will have to interwork with different systems.

4.5. Transport of Management Information

Transport of monitoring and management information should be provided as an integral part within the network. All types of "overhead" can for example be carried by dedicated WDM channels of each multiplex section.

5. Conclusion

These planning guidelines are regarded as first proposals to design a transparent Photonic Network for practical implementation. A "bottom-up" approach based on a reference configuration has been used for determining the maximum number of cascadable sections. Calculations indicate that large-scale core networks with high capacity can be realised. Transparent optical sub-paths for signals up to 10 Gbit/s, assembled in a 16-channel multiplex, can bridge distances of 400 km, and even longer distances with lower bitrates. Up to 10 transparent crossconnects are cascadable with ultra-high throughput of 2.56 Terabit/s (16 fibres times 16 wavelengths each transmitting 10 Gbit/s). Pre-requisites are WDM multiplexers and demultiplexers with sufficiently flat passband characteristics and sufficiently stable transmitters.

Considering the numerical results obtained, it can be concluded that a country of the size of Germany could be covered by a transparent Photonic Network.

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Transmission Characteristic of Arrayed Waveguide NxN Wavelength Multiplexer

Journal of Ligthwave Technology, Vol. 13, No. 3, March 1995, pp. 447-455

PART THREE

Network modelling

6

Intelligent Simulation for Computer Aided Design of Optical Networks[1]

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Summary

CATO (CAD Tool for Optical networks and interconnects) is a prototype tool for designing LAN/MAN packet-switching optical communication systems. CATO is a knowledge based tool that integrates Artificial Intelligence (AI) techniques and event driven simulation, for optimizing system cost and performance. CATO provides the user with an Optical Device Library (ODL), that contains functional and cost characteristics of the optical devices that can be used to design the optical system. The tool also supplies a user friendly Graphical User Interface (GUI) module, which allows easy specification, evaluation and optimization of the communication system under investigation. Taking into account user defined performance requirements and operational constraints of the optical communication system, CATO searches for the optimal design solution, consisting of the network topology, and the set of devices that minimize the overall system cost. By combining the device library, with AI and event driven simulation, to the best of our knowledge CATO provides the first iterative and automatic optimization procedure for the design of optical communication systems.

1. Introduction

Increasing communication speed requirements by applications such as video-on-demand and image library retrieval have created a great interest in very high speed networks and interconnects. Optical and all-optical solutions are being sought due to the expected Gigabits per second data transfer rates in these systems. Because more and more sophisticated photonic devices, such as Wavelength Division Multiplexing (WDM) add/drop multiplexers, crossconnects, and switches are being brought onto the market, the possibility for implementing and operating such optical high speed communication systems has become a reality. The design of these systems is a highly complex and challenging task, which cannot be carried out without the support of sophisticated Computer Aided Design (CAD) tools.

[1] This research was in part supported by the NSF under Grant Numbers NCR-9596242 and NCR-9628189.

Optical Network Design and Modelling H. van As & A. Jukan (Eds.)

In order to appreciate the usefulness of a CAD tool in the design of an optical system, let us describe the design process of an optical network as carried out today. The design process starts out by defining the overall system requirements. In the case of an optical network, this includes the type of communication medium, number of nodes, distance to cover, etc. Next, a network architecture and protocol are selected, and the topology of the network is laid out. At this point the network subsystems (e.g., nodes) are drafted, and appropriate optical devices are selected for each subsystem. Device experts play an important role in this selection process; the selection of the devices is done based on device characteristics provided by manufacturers in the form of data sheets, diagrams, etc.

The next step is to evaluate the system design using conventional simulation tools. The designer has to create a model of the system and supply it to the simulator. The level of detail of such a model may depend on the current state of the design, or the issues that are being investigated. But nevertheless, the model has to be complete in the sense that it should reflect all the relevant design decisions taken so far. Based on the performance results returned by the simulator, the designer has to evaluate the consequences of the design decisions. If the results are unsatisfactory, the designer has to make new design choices, modify the system's model and resubmit it for evaluation to the simulator. This process of iteratively making design decisions, modeling the system, and running simulations may be extremely time consuming. Even though the final results may be satisfactory, the designer has no guarantee that he has reached an overall optimal design, in terms of system performance and cost.

Currently, the only way to test the system (and to make the final component choices) is to purchase the devices and to create a testbed. This approach can be very expensive considering the high cost of optical components. It is also extremely risky, since the system may not work according to the required specifications with a given selection of components. In this case a new set of devices may have to be purchased and the testbed constructed anew. This costly procedure may require several iterations until a satisfactory prototype system has been built.

The objective of the CATO (CAD Tool for Optical networks and interconnects) project is to provide the designer with an intelligent software tool for the specification, design, simulation and optimization of optical communication systems. CATO allows the user to enter a set of design constraints and, based on these constraints, the tool will automatically complete a design, using a library with specifications of available (or expected to be available) components. The tool then iteratively evaluates the design using simulation techniques and decides on design alterations, using Artificial Intelligence (AI) techniques, until an overall optimal design is obtained. An intelligent tool can thus automatically evaluate a much larger set of possible designs than a designer ever would be able to do manually. It should be noted that due to the complexity of the analyzed systems, which may have many local optima, it cannot be guaranteed that the optimal solution is always found. In addition, the model may not reflect the actual behavior of the system due to modeling approximations. For these reasons only a suboptimal system design will be achieved. Nevertheless, in the remainder of this paper we will continue to use the term optimal.

Once CATO has produced an optimal design, the designer can use CATO's simulation facilities to further investigate the behavior of the design, for example by using different traffic characteristics or by introducing fault conditions. CATO supplies comprehensive system models, enabling the simultaneous evaluation of various system aspects, such as signal transmission, behavior of devices, access protocols, etc., and their interaction. On the basis of the simulation results the designer may decide to further refine the system design. Such simulation activities may reduce the amount of effort needed in the testbed evaluation phase.

Initial design and testing of a CATO prototype (CATO-1) has been completed recently. Its objective was to prove the feasibility of combining AI techniques and event driven simulation techniques with an optical device library, and a user friendly graphical user interface into a flexible CAD tool for obtaining optimal WDM communication network designs in terms of system cost and performance. CATO-1 is a prototype tool for designing packet-switching optical communication systems using a

LAN/MAN ring topology as the underlying network topology. It is a knowledge based tool that incorporates artificial intelligence techniques into a Network Constraint Engine (NCE), for optimizing cost and system performance. The two specific AI algorithms incorporated to achieve this goal are Simulated Annealing (SA) and a Genetic Algorithm (GA). In particular, CATO-1 finds an optimal number of transceivers for each network node, using a cost function that includes the cost of the devices and the overall system performance.

The purpose of this paper is to present the results of the CATO-1 development. The paper is structured as follows. In section 2, a survey of existing software tools in support of optical system design is given. In section 3, the concept of CATO-1 is described in detail. Separate subsections are devoted to each of the CATO-1 software modules. Also, the interfaces between the modules and the general flow of operation are described in separate subsections. In section 4 some typical results obtained with CATO-1 are presented. In section 5 conclusions from the CATO-1 development are drawn and directions for further work are given. Some background information on the applied AI algorithms is given in appendix A.

2. Survey of Existing Software Tools for Optical System Design

An optical communication system can be viewed as comprising of three layers:

- The **Network layer**, which refers to protocols, switching and routing mechanisms, control, management, fault monitoring and recovery, etc.
- The **Transmission layer**, which deals with issues related to signal transmission, including device factors that affect transmission, such as noise, crosstalk, dispersion, etc.
- The **Device (or physical) layer**, which refers to modeling and characterization of optical/ optoelectronic devices, and device technology.

Typically, existing design tools for optical systems are suitable for designing a single layer only. Therefore, the design of a communication system has to be carried out at each layer separately, essentially independently of the other layers. In this process for the design of one layer, basic requirements coming from other layers need to be considered, typically as fixed parameters. This methodology is not likely to lead to the optimal design of an all-optical network in terms of system cost and performance [1, 2].

The only commercial tools for optical design available on the market today are those for traditional ray-based imaging, 3-D lens modeling, and generic optomechanical designs. Well-known examples of such tools are LightTools and CODE V of Optical Research Associates (ORA). The popularity of those tools is a testimony to the fact that the field of classical optical and optomechanical modeling is mature, the design methods are well understood and hence CAD support is required for its numerous applications.

As a result of collaboration between the University of Illinois, ARPA and IBM, a prototype computer-aided design tool, iFROST, has been developed for mixed level modeling, simulation and analysis of data links and parallel fiber-optics buses [3]. It allows the user to specify the topology of the link or bus, component parameters, and then it interactively performs waveform simulations and analyses. Its application, however, is limited to single link or bus, and does not consider network configurations with switches and multi-wavelength (WDM) applications. IBM at T.J. Watson Center [4], Bellcore (MAGIC broadband design software), and others, are involved in some aspects of simulation, but only on the network layer. Conversely, a number of companies, such as AT&T, Corning, AMP, and Optikwerks, are involved in device modeling. Optikwerks, for instance, develops optical laser design software.

The Photonics Systems Group at NRC (National Research Council of Canada), is working on the development of simulation of fiber-optic communication links (Optical SPICE), guided-wave photonics (field distribution and propagation), and free-space photonics design tools for VLSI (Very Large Scale Integration) chip interconnects. Another academic research tool, OPALS (Optoelectronic, Photonic, and Advanced Laser Simulator) comes from the University of Melbourne, Australia [5]. In the United States, optical CAD research is also being carried out at George Washington University, Georgia Tech, the University of Colorado at Boulder, UC San Diego, and the University of Pittsburgh [6] using ad-hoc simulation tools as needed. The above research concentrates mainly on fiber-optics simulation and free-space optoelectronic design. Other examples of specialized academic tools include an optical interconnection cube simulator at the University of Arizona [7]; design of holographic memories for optical interconnection [8]; and tools for optoelectronic packaging [9]. The University of Colorado at Boulder is working on a number of tools to aid in the design of their optical systems: in particular a tool for system simulation in multi-hop optical networks; a general purpose simulator Xhatch, to aid in the design at the physical/device system level [10]; CAD tools for thermal modeling of the devices and modules, for the optical coupling between optical devices and optical fibers; and for the attachment of chips using soldering techniques.

Many general purpose network-level, protocol-oriented, simulators have been in existence since the late seventies. The list of such tools is too long to describe here in detail. Currently some of these tools are starting to incorporate protocols for optical networks. For a detailed description of the various university efforts in simulation of networks the interested reader is referred to recent conferences on simulation and networking.

In summary, there is currently no effort in the development of CAD tools for all-optical networks, or WDM communication systems, providing knowledge based design and specification that makes it possible to cross the boundaries between the various layers of network abstraction. Such CAD tools should be able to integrate a working model of the adjacent layers into the model of the layer being designed. Physical characteristics of devices from the device layer need to be considered in modeling, simulation and optimization of the transmission layer. The signal transmission model in turn must be used in the design of the network layer. This can be made practical by creating a single software tool that deals with the issues of the three layers, and an optical device library to provide a complete data base with specifications of optical components.

3. Description of CATO-1

As stated in the introduction of this paper, CATO-1 (the initial CATO prototype) combines AI techniques and simulation techniques with an optical device library and a graphical user interface to obtain optimal WDM ring network designs. To allow for a parallel development and to improve maintainability, CATO-1 is decomposed into the following four software modules:

- Network Simulation Engine (NSE).
- Network Constraint Engine (NCE).
- Optical Device Library (ODL).
- Graphical User Interface (GUI).

These modules and their (possible) interrelationships are depicted in Figure 1. The Network Simulation Engine (NSE) is a network simulator that implements a multi-channel WDM backbone ring network using a token passing protocol to co-ordinate channel access. Each node can have one or more transceivers, and amplifiers can be inserted in the links between nodes as needed. The Network Constraint Engine (NCE) is an optimization module that operates on the network specification and the simulation results to produce an optimal design. The NCE incorporates two different AI optimization algorithms: Simulated Annealing and the Messy Genetic Algorithm. (The user can select the algorithm to use.) The Optical Device Library (ODL) serves as a data base of optical devices that

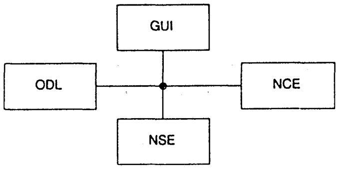

Figure 1: CATO-1 architecture

can be used in the network under design. The device specifications given in the ODL are used by both the NSE and the NCE, thereby avoiding duplicated storage of information. The user can add, modify, and delete devices in the ODL. The Graphical User Interface (GUI) allows the user to input parameters to the NSE and the NCE, and to update the ODL. The GUI displays all the results from the NSE and the NCE to the designer. In addition, the GUI is the control part of CATO-1; it controls the activation of the NCE and the NSE, and controls the communication between the NSE and the NCE by passing data between the two modules.

Sections 3.1 through 3.4 describe each of the CATO-1 modules in more detail. Section 3.5 summarizes the information exchanged between the CATO-1 modules and section 3.6 describes the operation flow of CATO-1.

3.1 Graphical User Interface

The Graphical User Interface (GUI) carries out the interaction between a user and CATO-1. Based on windows and pull-down menu's, this interface provides the user with a simple and intuitive way to enter the network optimization constraints, and the simulation parameters. The GUI provides a graphical representation of changes in the network under investigation. (Such changes may be initiated manually by the user, or automatically by the NCE.) The GUI also allows the user to operate on the device library.

The user gains control of the CATO-1 modules through a control window. This window contains a top level menu and a canvas screen. The top level menu offers the user a set of options for specifying the network architecture and the simulation parameters, for accessing the device library and for controlling the design activities. The canvas is used for monitoring the position of the network components. Network nodes are represented by circular shaped objects marked with the assigned node number. Amplifiers are represented by circular shaped objects marked with an "A". Fiber links are represented by straight interconnecting lines. A GUI window (without network layout) is shown in Figure 2.

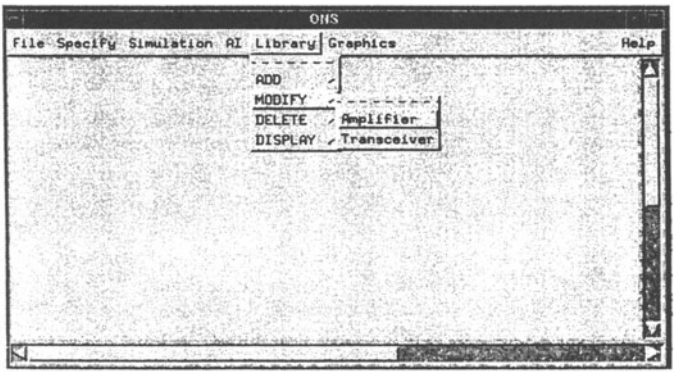

Figure 2: A GUI window

The graphical user interface of CATO-1 was designed using the Tcl/Tk programming language [11]. Tcl (Tool command language), developed by Ousterhout [12] and first released in 1989, is an interpreted language designed to be used as a common extension and customization language for applications. The Tk toolkit, first released in 1991, is a Tcl extension which provides a Tcl interface to the X Window System. It provides an easy way to build a graphical user interface to an application. Tcl/Tk provides a number of functions and widgets which simplify the design of a mouse driven graphical user interface. In addition, there are widget libraries for Tcl/Tk that extend the capabilities of the language. Since Tcl/Tk is designed using the C/C++ programming languages, it is inherently easy to integrate with C/C++ based application programs.

3.2 Optical Device Library

The Optical Device Library (ODL) serves as a data base of optical devices that can be applied in the network under design. Currently, the ODL contains only two types of devices: transceivers and amplifiers, but other types of devices can easily be added. Each transceiver consists of two parts: a transmitter and a receiver, each separately tunable on any of the available wavelength channels. That is, a transceiver can receive and transmit simultaneously on two different wavelengths. Their tuning time is assumed to be zero, i.e., they are instantaneously tunable, and their characteristics such as power, and noise values are assumed to be the same for all wavelengths. Some transceiver parameters and their typical values are listed in Table 1 (transmitter parameters) and Table 2 (receiver parameters).

Table 1: Transmitter parameters

Parameter	Typical value
Transmitting wavelength	1530 - 1560 nm
Maximum transmit power	+10 dBm
Long term wavelength stability	±1 nm
Price	4 kUS$

Table 2: Receiver parameters

Parameter	Typical value
Reception wavelength	1530 - 1560 nm
Sensitivity	-30 dBm
Maximum power	0 dBm
Equivalent noise input current	8 pA/√Hz
Price	3 kUS$

Currently, amplifiers are modeled as a simple signal boosting device. An amplifier has a flat gain over the wavelengths being amplified. The gain model for the amplifiers is:

$$\frac{P_{in}}{P_{sat}} = \frac{1}{G-1} ln\left(\frac{G_{max}}{G}\right), \tag{1}$$

where P_{in} is the total input power across all wavelengths to the amplifier, P_{sat} is the saturation power, G is the actual gain achieved, and G_{max} is the maximum small signal gain. Table 3 lists amplifier parameters and their typical values.

Table 3: Amplifier parameters

Parameter	Typical value
Frequency range	1530 - 1560 nm
Sensitivity	-30 dBm
Maximum small signal gain	+20 dB
Maximum total output power	0 dBm
Saturation power	-10 dBm
Noise figure	6 dB
Price	20 kUS$

3.3 Network Simulation Engine

The Network Simulation Engine (NSE) models an all-optical WDM multi-channel backbone ring LAN/MAN, based on SCM-NET [14]. The ring network consists of M nodes interconnected by means of unidirectional fiber optic links. Optical amplifiers may be incorporated in the links to compensate for power losses due to the fiber links and the nodes themselves. An example of a six node ring with one amplifier is shown in Figure 3. Using wavelength division multiplexing, N data

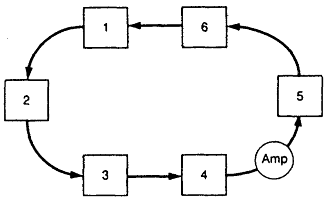

Figure 3: Example of a 6 node ring

channels of 1.2 Gbps plus one control channel of 100 Mbps are created on the fiber links. The maximum number of nodes is currently set to 15 and the maximum number of channels to 8, reflecting present day technology constraints. As technology evolves these maxima can be easily increased in the model. Each of the M nodes on the ring is equipped with K transceivers (1 <= K <= N), depending on for instance the node's traffic requirements. In addition to transmitting and receiving, nodes have the capability to relay data channels and to strip data channels. The channel relay function is needed to provide all-optical connections between arbitrary source/destination combinations and the channel stripping function is needed to remove data from the channel (after it has made a complete trip around the ring). The control channel is used to provide access to the data channels. The access protocol is based on a multi-token extension of the FDDI token passing protocol [15], with the extension that a node is allowed to hold multiple tokens at the same time. The control channel itself operates as a slotted ring [16], where slots of fixed length are either empty, or contain a token. The architecture of a node is shown in Figure 4. In this architecture, the Node Manager performs the token passing protocol function and controls the operation of the channel stripping function and the tuning of the transceivers to the data channels.

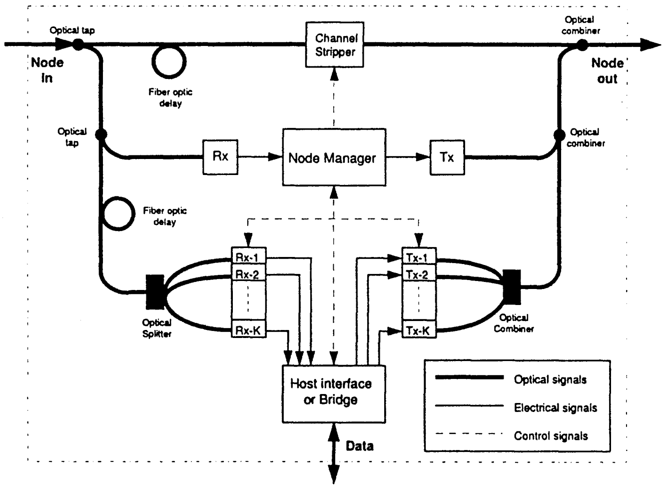

Figure 4: Node architecture

The control channel carries a number of tokens equal to the number of data channels, i.e., N. Each token has a length of 4 bytes and contains the data channel identification, the status bit ("free" or "busy"), the destination address, the source address, and the acknowledgment (ACK) bit. The reception of a free token indicates that the associated data channel is available for data transmission and the reception of a busy token indicates that the associated data channel is being used for data transmission. The operation of the token passing protocol is shown (slightly simplified) in Figure 5.

Every node with a packet to transmit waits for a free token on the control channel. Whenever a free token is received, the node checks whether it has a free transmitter, and if so, tunes the transmitter to that channel and puts the intended destination address in the token to indicate to the remote node that a packet is coming on that particular channel. The node starts transmitting after the captured token has been transmitted. The source node releases a free token after completion of transmission of the packet.

Whenever a node receives a busy token, it checks whether it is intended for the node itself. If so, it checks whether it has a free receiver, and it tunes the receiver to the wavelength of the channel

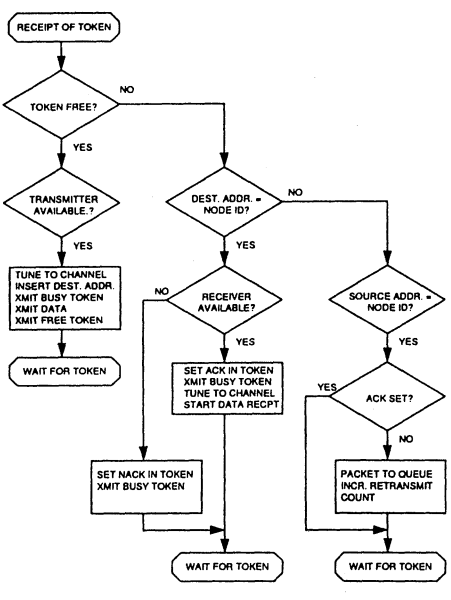

Figure 5: Token passing protocol

specified in the token, turns the ACK bit on in the token and releases the token. If the node does not have a free receiver, it turns off the ACK and releases the token. When the token has traveled back to the source node, it checks whether ACK has been set or not. If there is no ACK, the source moves the packet back onto the queue of packets to be transmitted. Otherwise, it removes it from its buffers. Finally, the returned busy token is purged.

A packet might fail to reach its destination due to two reasons:

- The destination has no free receiver to tune.
- The optical power in the communication link is inadequate or the Signal to Noise Ratio (SNR) at the receiver end is too low.

In the first case, the packet will be retransmitted as the node will not give an ACK. In the second case, the node will give an ACK (which has been given as soon as the receiver is tuned before starting to receive). The NSE records the number of packets that failed to reach their destination, along with the reason for failure of reception.

The NSE is designed as an event-driven simulator. Every event which results in a change of the overall network state is modeled, and the simulation runs by serially executing these events in temporal order. The NSE can also be used as a stand-alone simulation tool for evaluating the performance of the optimized system under different operating conditions, e.g., various arrival rates.

3.4 Network Constraint Engine

The Network Constraint Engine (NCE) is responsible for optimizing the network specification that has been entered by the user. Basically, it determines an optimal number of transceivers for each node on the ring network, based on its input from the simulator (NSE) which provides the failure rate of packet reception at each node of the network. As described in the previous subsection, there are two possible scenarios for failure of packet reception: 1) unavailability of a receiver and 2) inadequate optical power in the communication link or low SNR at the receiver. Based on the number of packets lost due to unavailability of a receiver, the NCE can assign additional transceivers at the individual nodes in order to reduce the retransmit count (and hence the average packet delay time). The NCE could use the number of packets lost due to low power, or low SNR to place amplifiers on the ring. Although all the necessary provisions within the GUI, ODL, and NSE modules are available, this last functionality is however not yet implemented in the NCE.

The NCE can use two different AI algorithms for transceiver placement, i.e., Simulated Annealing (SA) [17] and a Genetic Algorithm (GA) [18], selectable by the user. Appendix A provides a brief introduction to these two algorithms. SA and GA were chosen in favor of other optimization methods such as neural networks and fuzzy logic, because no training with existing data sets is required. The SA algorithm implemented in the NCE is the Adaptive Simulated Annealing (ASA) algorithm developed by Ingber [19], which is made publicly available under a GNU copying license. The ASA code was first developed in 1987 as Very Fast Simulated Reannealing (VFSR) [20]. In 1993 many adaptive features were developed, leading to the present ASA code. ASA is now used world-wide across many disciplines. Other examples of the application of SA in the design of communication networks are presented in [21, 22]. The GA implemented in the NCE is the Messy GA (MGA)

developed by Goldberg, Korb, and Deb [23]. The most important difference between MGA and traditional GA is that MGA uses variable-length chromosomes that may be over- or under specified with respect to the problem being solved. In addition, MGA uses simple cut and splice operators instead of fixed-length crossover operations (see appendix A). NCE uses the MGA coded in the C language [24].

To optimize the number of transceivers, the NCE calls the selected AI algorithm to optimize a cost function. This cost function is based on the information that was passed from the simulator (i.e., the number of packets lost due to unavailability of receivers). The cost function associated with each AI algorithm is:

$$A * (\ \%\ lost\ packets\ ) + B * (\ total\ \#\ of\ transceivers / X\ ), \tag{2}$$

where A and B are (currently) fixed weights and

$$X = M*N \quad (1 <= N <= 8,\ 2 <= M <= 15), \tag{3}$$

equals the maximum total number of transceivers allowed in the system under study. M is the number of nodes in the system and N is the number of data channels. Variable X biases the optimal solution towards a higher number of transceivers, when more data channels are available. Equation (2) is optimized under the constraints:

$$\#\ of\ transceivers\ for\ node\ i <= N \quad (1 <= i <= M) \tag{4}$$

In the current implementation, the NCE optimizes the number of transceivers using only the device types provided by the designer, e.g., it does not intermix different types of transceivers. Optimization over different types of devices has to be done manually by the designer, by selecting in successive iterations different device types and finally choosing the device types for which the lowest cost function is achieved.

3.5 Information exchange

Table 4 gives summary descriptions of the information exchanged between the CATO-1 modules.

Table 4: Information exchanged between the CATO-1 modules

From	To	Information transferred
GUI	NSE	Network specification, including number of nodes, distances between nodes, number of data channels, number of transceivers at each node, fiber specifications, and device specifications. Simulation parameters, including traffic characteristics, total number of packets to be transmitted and initial token locations.
NSE	GUI	Simulation results, including the number of lost packets for each node, positions in the ring where power or SNR dropped below an acceptable level, average queue lengths, average message delays, and the network throughput.
GUI	NCE	Identification and prices of devices that are used in the network. Simulation results.
NCE	GUI	Final value of the cost function for the optimal network. Number of transceivers at each node. Dollar cost of the network.

The exchange of information between the NSE, the NCE, and the GUI is accomplished through predefined ASCII formatted data files. Since the GUI controls the interactions, files are always passed between modules via the GUI. The formats of the files are know to the GUI and can be read

by the GUI as well. On user demand, the GUI displays the information from these files in predefined windows.

3.6 Flow of operation

The typical flow of operation in the design process is depicted in Figure 6; it shows the usual cycling through the CATO-1 states. Three operational states are distinguished within CATO-1, i.e., the GUI state, the NSE state and the NCE state. Each of these states is now briefly described.

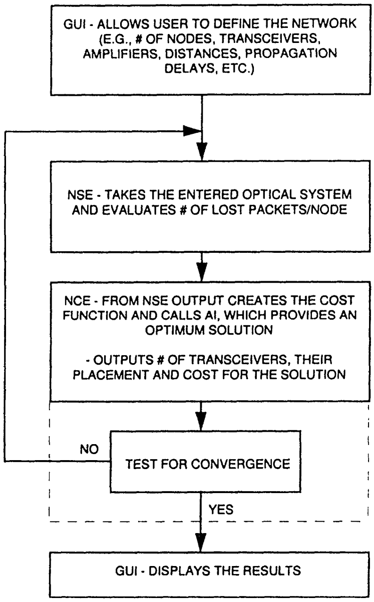

Figure 6: CATO-1 flow of operation

GUI state. In this state, CATO-1 allows the designer to define a network specification. The inputs to be specified include: number of nodes, distances between nodes, number of transceivers at every node, transceiver type, number of amplifiers and their positions on the ring, amplifier type, the number of packets generated during simulation, and the method of optimization to be used. An output file is generated, including all the information required by the NSE to run a simulation.

NSE State. In this state, the NSE receives the input data from the GUI and the simulation is run. The simulation will stop once the total number of packets specified in the GUI state have been transmitted. An output file is generated containing the results of the simulation. The number of packets lost at every node is presented in tabular format, together with an indication why the packets were lost.

NCE State. The file generated during the NSE state is used as input by the NCE. Based on this file and on the method of optimization specified in the GUI state, an AI algorithm is executed. After a number of iterations an output file containing the number of transceivers to be used at every node is generated. The results are presented to the designer in tabular format.

4. Results

CATO-1 has been programmed in the C programming language. It consists of over 7400 lines of code (excluding the AI algorithms), divided over the modules as follows: GUI: 3400 lines, NCE: 2000 lines, NSE: 1600 lines, and ODL: 400 lines.

A number of network design experiments were carried out with CATO-1 on a Silicon Graphics Indy, with R5000 processor and 64 Mbyte of RAM. In terms of the network cost and design the ASA and MGA produced similar results. The main difference was the execution time. For a particular test case MGA required about 2 hours to attain the results while ASA took only about half a minute. It should however be noted that MGA achieved 90% of its final result in about the same time that ASA executed. MGA and ASA performed consistently the same for different network configurations and traffic characteristics. Ingber also made a comparison study between SA (VFSR) and GA [25]. For a suite of six standard test functions he found that VFSR performed orders of magnitude more efficient than GA. These results are however not conclusive enough to discard MGA for future CATO developments. In CATO-1 only one type of transceiver is used throughout the system, resulting in fairly simple constraints. This may have caused the cost function evaluation to be weighted in favor

of ASA over MGA in terms of performance. If an intermix of devices was allowed, the complexity of the constraints would increase and this could effect the comparative performance of the two algorithms. An exhaustive re-examination of the two AI methods under a variety of design problems is therefore required for future CATO developments.

5. Conclusion

The development of an initial CATO (CAD Tool for Optical networks and interconnects) prototype proved the *feasibility* of intelligent CAD software for designing optical networks and interconnects considering performance aspects of both network and transmission layers. This first prototype (CATO-1) is a tool for designing packet-switching optical communication systems using a LAN/MAN ring topology as the underlying network. It incorporates Artificial Intelligence techniques for optimizing system performance and cost. The two specific algorithms incorporated to achieve this goal are Adaptive Simulated Annealing (ASA) and Messy Genetic Algorithm (MGA).

The tool supplies a user friendly Graphical User Interface (GUI) module which allows easy specification, evaluation and optimization of the communication system under consideration. It also provides the user the capability to maintain a simple Optical Device Library (ODL), such that devices can easily be added, modified, or deleted. CATO-1 also contains a Network Simulation Engine (NSE), which allows the Network Constraint Engine (NCE) to provide an iterative and automatic optimization procedure of the communication system design. The NCE is responsible for determining the optimal number of transceivers at each node in the network. It takes its input from the NSE which provides the number of packets lost at each network node due to unavailability of transceivers and places additional transceivers in order to minimize a cost function, which includes the cost of the transceivers and the number of lost packets.

The major conclusion regarding further needed research is that photonics is a rapidly growing field which affects many important applications, such as communications, networking and interconnections, data storage, image processing, etc. It is still a relatively new field, and thus lacking many of the design tools that are available to electrical engineers. Specifically there is a lack of tools on the market to support optical system designers with the specification, design, simulation, performance analysis and optimization of optical/photonics systems.

The goal for further research will be to fill this gap by providing a CATO-1 based software tool for *virtual prototyping* of photonics systems for these emerging applications. In particular, all-optical communication systems based on Wavelength Division Multiplexing (WDM) and multi-wavelength routing technology are among the most promising and fastest growing areas. The next versions of CATO will significantly reduce the time needed to design such photonics systems. Based on the design constraints provided by the user, CATO will automatically complete an optimal design, using mathematical programming techniques (linear, integer, and dynamic), intelligent search methods and AI. CATO will relieve the user of manually evaluating each design alternative, thereby allowing him/her to concentrate on the critical aspects of the system design. The simulation facility of CATO will enable the analysis of each system layer separately, but also the combined analysis of multiple system layers, and their interaction. We believe that this will reduce the amount of effort needed for constructing and evaluating a working testbed. Overall, the application of CATO is expected to significantly reduce the cost of designing photonics systems.

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APPENDIX A AI METHODS

This appendix gives a brief overview of Simulated Annealing (section A.1) and Genetic Algorithms (section A.2). The text and figures in this appendix are largely based on reference [26].

A.1 Simulated Annealing

Simulated Annealing (SA) [26] exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum of a cost function. SA's major advantage over other methods is the ability to avoid becoming trapped at local minima. SA is based on an algorithm developed by Metropolis et al. [27].

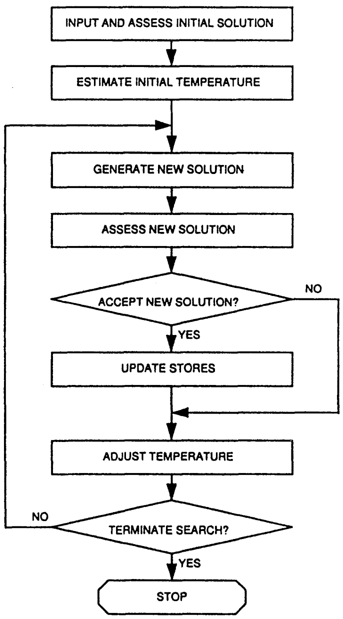

Figure 7: Basic structure of the Simulated Annealing algorithm

Figure 7 shows the basic structure of the SA algorithm. SA generally begins by reading in an existing solution to the problem or generating a random solution. Once the starting temperature and termination criteria have been established the actual annealing begins. At each iteration, the current solution is randomly perturbed to create a new solution (this step is referred to as a "move"). If the constraints are not satisfied by this configuration, the move is immediately rejected. Otherwise, the change in cost δC from the previous to the new solution is calculated, and the move is accepted if a randomly drawn number in [0, 1) is less than (or equal to) $exp(-\delta C/T)$. All moves which lead to a decrease in cost will be accepted; moves leading to an increase will be accepted with a probability which depends on the increase and the current temperature. If the move is not accepted, the previous solution is restored. After a certain number of moves the

temperature will be decreased, thus decreasing the probability of accepting uphill moves. The algorithm terminates when the specified stopping criterion is met, e.g., when no improvement has been found for some number of moves.

The manner in which the temperature T is decreased over the iterations is referred to as the cooling schedule. Many schedules have been proposed, but the simple geometric schedule works fairly well on a variety of problems. In this schedule the temperature is reduced by multiplying it with a constant factor smaller than 1 (e.g., 0.99) at each chain of moves. The chains are of equal length.

A.2 Genetic Algorithms

Genetic Algorithms (GAs) [26] are optimization techniques based on the phenomenon of natural evolution. In natural evolution each species searches for beneficial adaptations in a changing environment. As species evolve new attributes are encoded in the chromosomes of individual members. This information does change by random mutation, but the driving force behind evolutionary development is the combination and exchange of chromosomal material during breeding. The original concepts of GAs were developed by Holland [28].

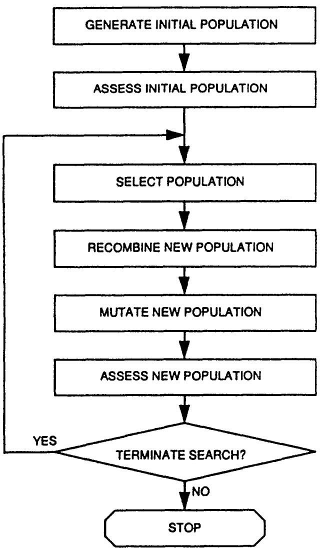

Figure 8: Basic structure of a Genetic Algorithm

The basic structure of a GA is shown in Figure 8. When applied to a cost function that needs to be minimized, the variables are represented as genes on a chromosome. GA searches from a group of candidate solutions (population) to another, rather than from individual to individual (as e.g., Simulated Annealing does). Through natural selection and the genetic operators - recombination and mutation - chromosomes with better fitness (i.e., a lower value of the cost function) are found. In the natural selection step, the chromosomes with the largest fitness scores are placed one or more times into a mating subset in a semi-random fashion. Using the recombination operator, the GA combines genes from two parent chromosomes to form two new chromosomes (children) that have a high probability of having better fitness than their parents. The two most common recombination operators are the one-point and two-point crossover methods. In the one-point method, a crossover point is selected along the chromosome and the genes up to that point are swapped between the two parents. In the two-point method, two crossover points are selected and the genes between the two points are swapped. The children then replace the parents in the next generation. The purpose of mutation is to provide insurance against the irrevocable loss of genetic information and hence to maintain diversity within the population. A mutation simply changes the value for a particular gene. GAs offer a generational improvement in the fitness of the chromosomes and after many generations create chromosomes containing the optimized variable settings.

The Need of Wavelength Conversion in All-Optical Networks

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Abstract

Different optical path accommodationn design algorithms are analysed and discussed. Approaches using a rearrangment of wavelengths in each link are also proposed. The results show a drastic reduction of wavelength converters in each node.

I - INTRODUCTION

An optical path is a semi-permanent connection between path end points utilising optical cross- connects (OXC). In the literature two different approaches supporting optical paths have been introduced: virtual wavelength path (VWP) and wavelength path (WP), depending on whether the signal is carried by the same wavelength during its travel throughout the network or is converted to another in midstream. There is a significant debate in progress about the need of translating the wavelength of a signal within a network.

Different papers [1-3] in the literature show that, in real network structures, the implementations with and without wavelength translations require almost the same number of wavelengths. On the other hand, it has been also demonstrated that WP scheme incurs larger optical cross-connect (OXC) system scale than VWP scheme [4,5].

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Moreover, it has been shown that the difference between WP and VWP schemes increases as the number of wavelengths carried on each fiber increases. This means that, even if the overall number of wavelengths is almost the same for the two approaches, the technological limitations, expressed as a maximum number of wavelengths which can be carried on the same fibers, cause a meaningful difference between the VWP and WP schemes, in the number of ports of the OXC's.

The optical path accommodation algorithm is a crucial point for the construction of a cost effective network. In general, these algorithms are basically composed of two steps: i) searching of the path route; ii) assignment of the wavelengths. In the VWP only the first step is needed. In fact, wavelength assignment is a trivial issue since each network link is independent of each other. On the other hand, in the WP both the problems have to be solved simultaneously throughout the network.

If the number M of wavelengths per fiber is limited, each link consists of multiple fibers, so a link is defined as a bundle of fibers between two adjacent OXC's. Each OXC has two types of ports: one runs to adjacent OXC's in different nodes ("inter-office ports"), the other connects to the electrical cross-connects (DXC) in the same node and accommodates the adding/dropping paths terminated at the node ("intra-office ports"). It is desirable that optical path (OP) be set-up in the network so as to minimize the total number of ports required at each node, that is the wavelength utilisation efficiency in link must be maximised. Thus the objective function is to minimize the mean value of number of ports in the network: here the number of ports at each node is defined as the summation of the number of inter-office ports (N_1) and intra-office ports (N_2) at the node:

$$N=N_1+N_2.$$

In this paper we report an analysis of the algorithms which allows the implementation of VWP and WP schemes, and compare their performances in terms of N, N_1, and N_2. Then we propose a rearrangement algorithm which allows the performance of VWP scheme to be reached, with a strongly reduced total number of wavelength converters with respect to the one corresponding to VWP. This permit a significant reduction of the OXC costs. In section II and III the accommodation design algorithms corresponding to VWP and WP schemes, respectively, are briefly reported. In section IV we compare the performances of VWP and WP schemes, while in section V we report the novel rearrangement algorithm which we propose, together with some relevant results. Finally, in section VI some concluding considerations are reported.

II - VWP ACCOMMODATION DESIGN ALGORITHM

Let A be the path request matrix, wherein the value of the entry (i,j) indicates the number of paths connecting the node i to the node j ($0 \le i, j \le N$, wherein N

is the number of network nodes). We suppose that A is symmetrical, i.e. if a path request exists from i to j, there also exists a request from j to i. The summation of all the elements of A is named Traffic Volume and corresponds to the total number of paths to be set up within the network. Finally, let p_i be the number of paths accommodated in the link i ($0 \le i \le NL$, being NL the number of network links).

As above mentioned, in the VWP scheme, only the path routes have to be found. Once the routing has been established, the final number of paths per link p_i ($0 \le i \le NL$) and the number of terminating paths per node T_j ($0 \le j \le NL$) have been also determined, so the inter-office port requirements for each link N_{1i} is directly determined by $\lceil p_i / M \rceil$, whereas the number of intra-office ports per node N_{2j} is determined by $\lceil T_j / M \rceil$.

The algorithm, sketched in fig. 1, consists of the following steps.

STEP1 - The initial path routes are set-up path so as to minimize the summation of $\mathbf{p}_i$, for each path and the set {NL} of network links for which $\mathbf{p}_i = \max (p_i, 0 \le i \le NL)$ is determined. The links belonging to this set are called "maximum links", they correspond to those links which support the maximum number of paths.

STEP2 - We reroute the paths that contain the maximum number of maximum links. This rerouting is carried out so as to make lower the cardinality of the set {NL}.

STEP3 - The most inefficient links are found; these links are those with the minimum value of $\mathbf{C}_i = \mathbf{p}_i \bmod \mathbf{M}$, i.e. those links characterised by the highest waste of frequencies.

STEP4 - The paths containing the maximum number of inefficient links are found: these are the candidates for the rerouting.

STEP5 - The paths determined in the previous step are rerouted by applying Dijkstra's algorithm, employing the weighting function $\mathbf{W}_i$ for the i-th link ($0 \le i \le NL$):

$$W_i = \begin{cases} p_i & (C_i = 0) \\ 1/C_i & (C_i \neq 0) \end{cases}$$

III - WP ACCOMMODATIONN DESIGN ALGORITHM

In the WP scheme, the wavelength assignment problem must be solved: first we optimise path routes, then we assign wavelengths separately. The algorithm, whose flow-chart is shown in fig. 2, involves the following steps.

STEP1 - Route each path using VWP accommodation design procedure.

STEP2 - Divide the obtained path routes into the minimum number of sets of routes (we call them "layers"), such that the links in each layer must be occupied by as many WP routes as possible and no WP routes in one layer share any link. Let L be the number of layers.

STEP3 - Allot a layer number (1~L) randomly to each layer so that each number appears once.
STEP4 - Assign a wavelength (M is the number of wavelengths within a fiber) cyclically to each layer according to the layer number. Wavelengths are assigned as follows: λ_1 to the paths in layer #1, λ_2 to the paths in layer #2, λ_M to layer #M, λ_1 to layer #M+1, λ_2 to layer #M+2,...From this wavelength assignment, we determine the number of inter-office ports N_1 and intra-office ports N_2 for each node in the network.
STEP5 - Obtain the average number of total ports N in the networks, according to the wavelength assignment performed in STEP4.
STEP6 - Iterate STEP3~STEP5 a certain number of times, finding the optimal layer assignment that give the minimum average value of N.

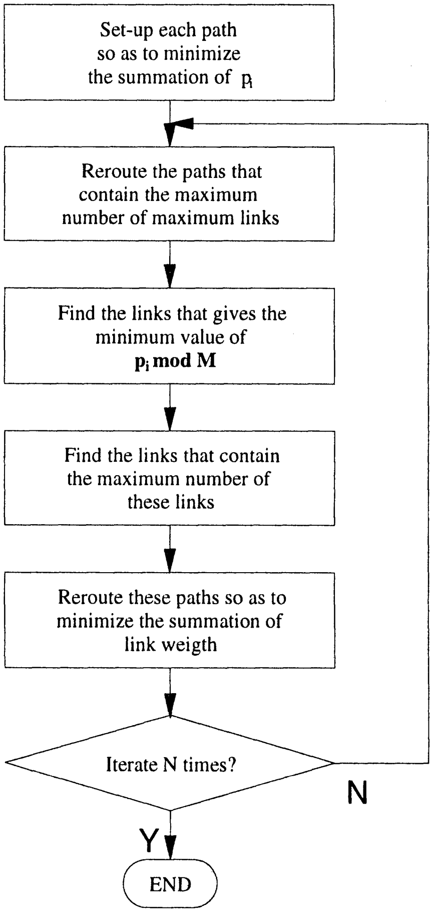

Fig. 1 - VWP accommodation design algorithm

IV - PERFORMANCE COMPARISON BETWEEN THE DIFFERENT ACCOMMODATIONN DESIGN ALGORITHMS

A relevant example of the performances of the two approaches reported so far, namely VWP and WP, are reported in figures 3 ~ 6, considering a maximum number of channels per fiber M equal to 4, 8, 16 and 32, respectively, in a 4X6 poligrid network.

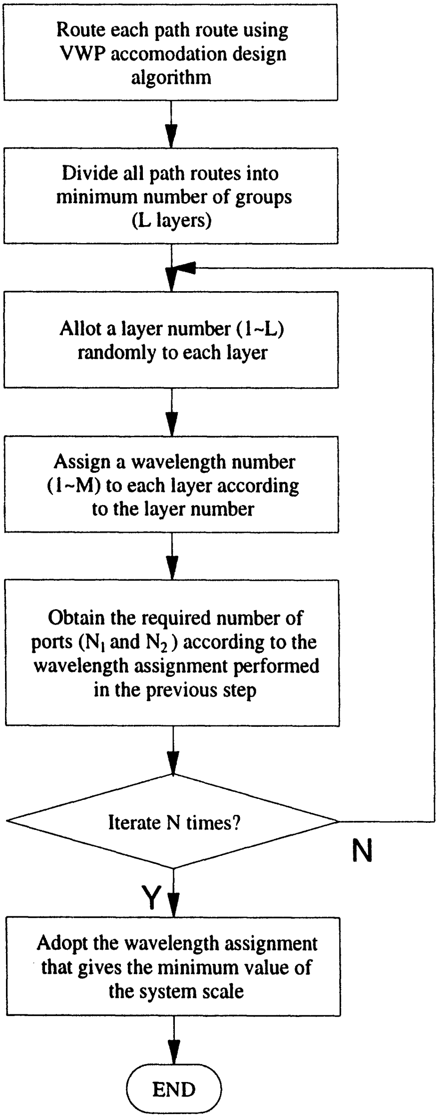

Fig. 2 - WP accommodationn design algorithm

In particular the average number of ports per node is reported for different traffic volumes (total number of active paths). Each point is obtained averaging among many possible traffic patterns (obtained by randomly selecting terminating node pairs). It is worth observing that in any considered traffic volume, the average number of ports, in the case of VWP, is smaller than the corresponding one related to WP scheme. This is true either considering the total number of ports N, or considering the inter-office ports N_1 or the intra-office ports N_2.

In particular, comparing the different figures, it can be noticed that, when M becomes large, such a difference is much more evident.
The algorithms previously proposed show that the WP-based OXC requires a number of ports which is larger than that of VWP-based OXC, when the number of wavelengths multiplexed into a fiber is restricted. This means, altogether, that wavelength conversion allows the dimensions of the OXC to be reduced of a certain amount, which varies case by case.
However, we can imagine that a limited number of wavelength conversions, per each optical path, would allow the reduction of the OXC dimension towards the ones obtained through the VWP. In other words, it could be possible to obtain the same performance of the VWP scheme, in terms of medium number of ports per OXC, with less wavelength converters inside the nodes, with a consequent decreasing of the costs and complexity of the OXC themselves.

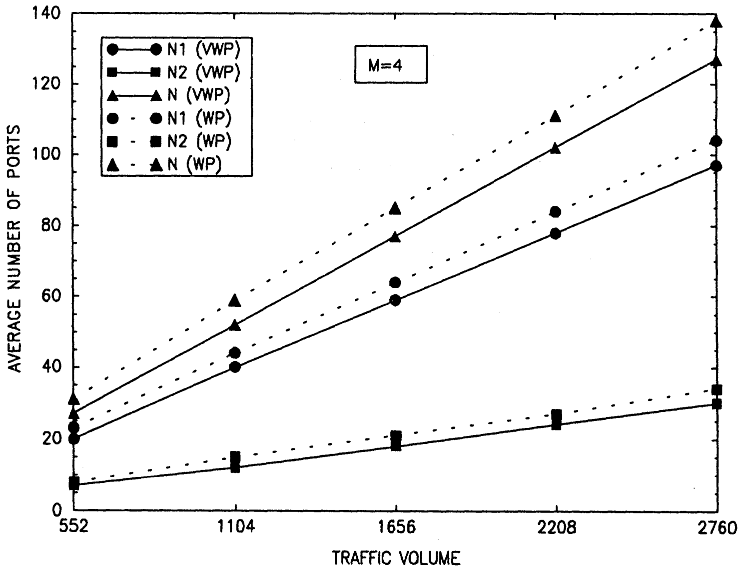

Fig. 3 - Average number of ports in the case of M=4

A first attempt, to investigate intermediate optical path schemes, was based on the following considerations. A long optical path, associated at a given wavelength, can be splitted in more than one sub-paths, each with a proper wavelength that can differ from each other. The length of each sub-path, expressed as the number of crossed OXC (hops), is limited to a given integer b. This means that the splitted paths are shorter than b hops. Each b hops a wavelength conversion occurs. Thus the path splitting generates some sub-paths, to which wavelength assignment procedure is applied, as in WP algorithm. We can call such a scheme as b-WP, where b denotes the maximum sub-path length.

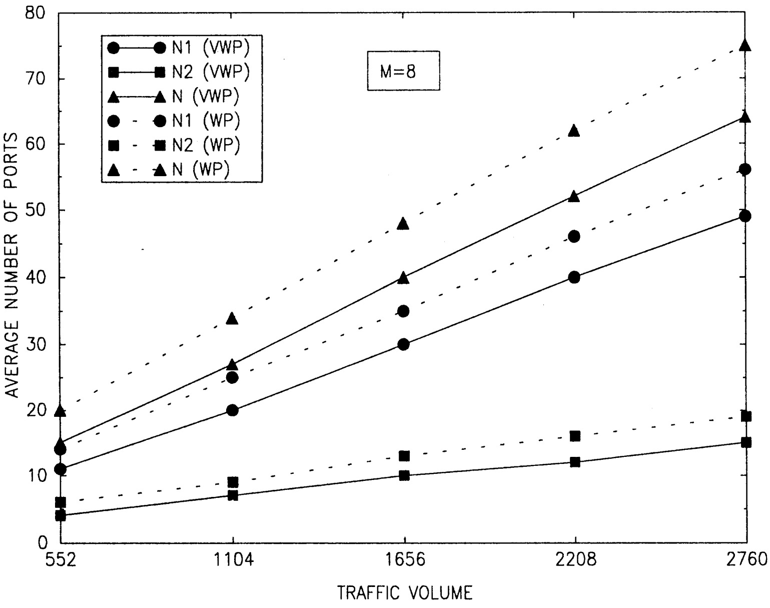

Fig. 4 - Average number of ports in the case of M=8

The results showed us that, as expected, the performance obtained through b-WP schemes are somewhat intermediate between VWP and WP. However, such an approach is not effective for the following reason. The WP scheme causes that some fibers are scarcely utilised. This means that, in a general optical path, some links could be scarcely utilised. The b-WP approach does not consider when it is necessary to put wavelength conversion, but simply split in different sub-paths a main path. This is an uneffective way to proceed. A better approach is proposed in the following section.

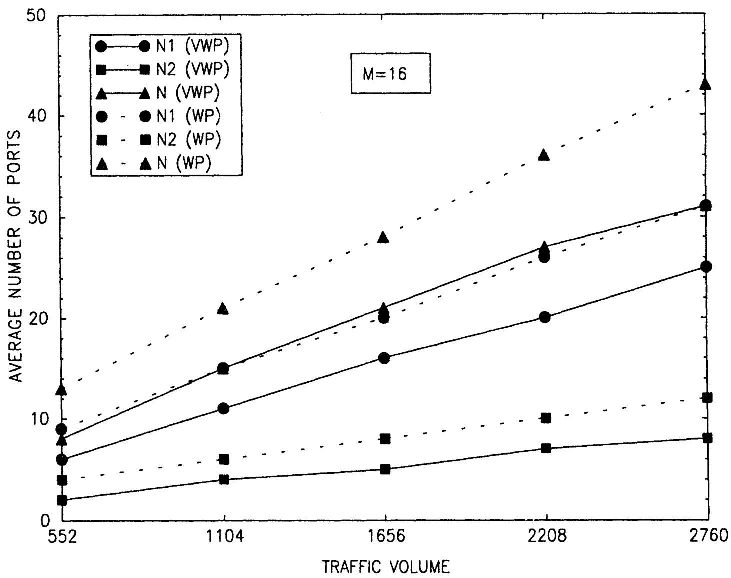

Fig. 5 - Average number of ports in the case of M=16

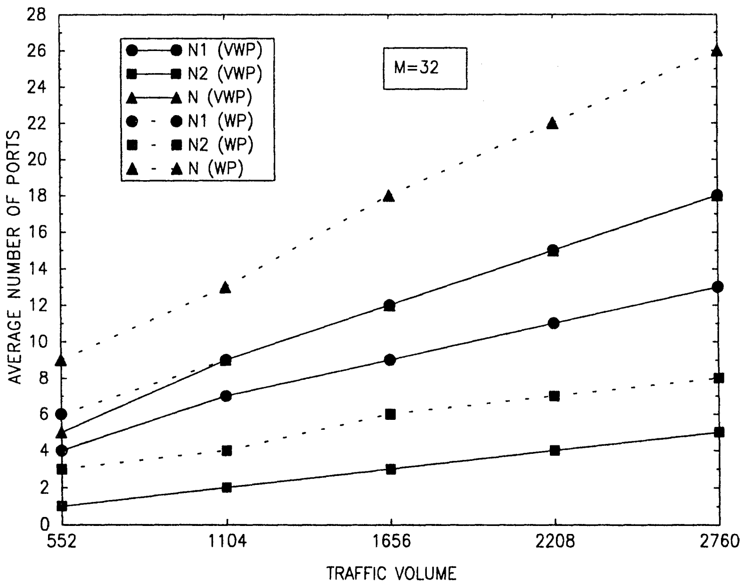

Fig. 6 - Average number of ports in the case of M=32

V - REARRANGEMENT ALGORITHM

We propose an algorithm that allows to rearrange the distribution of wavelengths in the fibers of each link, so as to eliminate in each link some fibers that are scarcely utilized: this procedure reduces the number of inter-office ports N_I in each node. Anyway a similar procedure can be applied to reduce the intra-office ports. The algorithm starts from wavelength assignment to optical paths in each layer (WP scheme): so it is possible to determine the mean value of N_I in the network. Moreover, we can observe that the wavelength assignment imposes, in each link, a number of fibers greater than the VWP scheme and induces a non efficient use of wavelengths in the fibers, since it's possible that a part of the wavelengths in each fiber have been assigned to some paths.

Let fibers of each link be numbered from 1 to n; let M_i be the number of wavelengths that are used and M_i' the number of non used wavelengths in the fiber #*i* ($M_i + M_i' = M$, where M is the number of wavelengths in each fiber). However if, in the fiber #i of a certain link, the number of used wavelengths M_i is less than or equal to the number of non used wavelengths in previous fibers (i.e. $M_i \le \sum_{j=1}^{i-1} M_i'$), it's possible to assign to each of M_i paths of fiber #i one of the non used wavelengths of other fibers: this can be realized by introducing , for each wavelength shifting, a converter in each node at the extremity of the link. If it's possible to shift the M_i wavelengths, we can eliminate the fiber #i from the link. This reduction of the number of fibers in each link allows us to obtain in each node a value of N_I equal to VWP scheme, using a very small number of converters. So we can count the total number K of converters in the nodes of the network and determine the "Wavelength Conversion Percentage Amount" (**WCPA**), defined as:

$$\mathbf{WCPA = K / (N_I\, M)}$$

where N_I is the mean value of inter-office ports in WP scheme.

Such an algorithm allows the total number of wavelength converters to be drastically lowered. In fact, fig. 7 illustrates the WCPA versus the traffic volume, for different values of the number M of wavelength carried by each fiber. Even in this case, each point of any curve is obtained by averaging the values obtained for many traffic patterns associated to a given traffic volume.

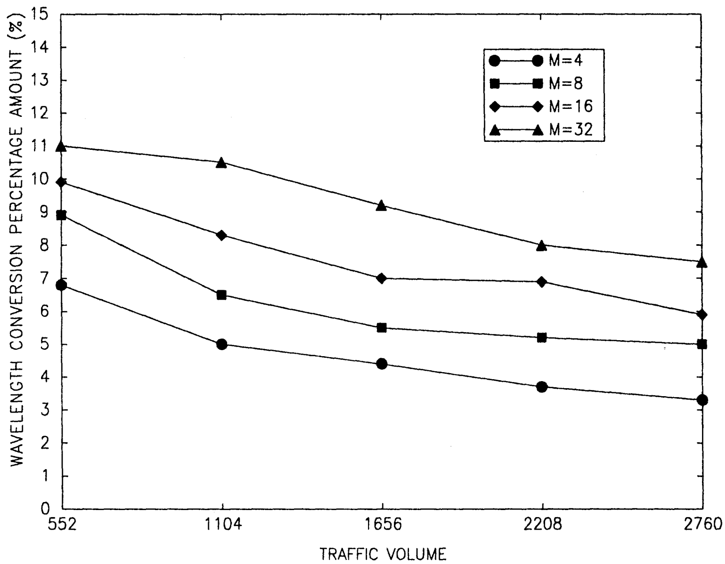

Fig. 7 - Wavelength Conversion Percentage Amount

The main result is that, adopting the considered approach, we can obtain the same performance of VWP scheme, using something like the 10 % of the number of converters which are used with VWP scheme.

VI - CONCLUSIONS AND PERSPECTIVES

Wavelength conversion allows the reduction of optical cross-connect system scale (number of ports). However, the employment of VWP scheme brings about a big number of wavelength converters inside the node, with a consequent increasing of complexity and costs. We have shown a possible algorithm that allows the number of converters to be drastically reduced, by locally solving the uneffective utilisation of the fiber links. Even this approach is not optimum and can be further improved by properly designing the network. This is the goal of further research. In any case the employment of a reduced number of converters demands for suitable OXC architecture, in which any number of converter can be used without altering the function of the node itself.

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PrimeNet - A concept to apply Arrayed Waveguide Grating Multiplexers in a WDM-based fiber backbone

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Abstract

This paper presents a concept for a Multi-Gbit/s WDM-based fiber backbone. The backbone interconnects stations by the means of an Arrayed Waveguide Grating Multiplexer (AWGM). The architecture offers the possibility to evolve from unidirectional virtual ring structures to a fully meshed interconnection. A SONET/SDH based system architecture and a strategy to map ATM service classes on it is proposed.

1 INTRODUCTION

The basic goal in broadband networking is to deliver high bandwidth at low latency [1]. Optical data transmission is the natural candidate to reach that goal. Over the last few years Wave Division Multiplexing (WDM) has been seen as a proper workaround for the electro-optical bottleneck, i.e. the low electronic processing speed (a few Gbit/s) compared to the high possible bandwidth of a single fiber (several Tbit/s). WDM networks are often recognized as circuit switched networks, because of the long laser tuning times and the aim to provide a "dark fiber" to the end user. The disadvantages of circuit switching are well known (reservation for the peak rate...), but currently outweighed by the plenty of bandwidth WDM is able to provide. This paper emphasizes the combination of Time Division Multiplexing (TDM) and WDM to allow for a packet switched optical network. We develop a concept to interconnect a set of interconnecting devices across an AWGM. The basic idea is to leave the routing decisions within the electronic domain, so that there is no wavelength conversion necessary. While the routing has to be performed in an attached

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(electronic) packet router or switch, the wavelength channel is divided into time slots which can be used through an access protocol. That way a flexible allocation of the bandwidth is made possible in contrast to the use of a circuit based SDH scheme. The basic element of the network is introduced in chapter 2. It enables to set up a logical ring on each wavelength which can be operated independently. The resulting station design and several possibilities to share the bandwidth between the attached stations are shown in chapter 3 and 4, respectively. The crucial issue of connecting several of these networks of several parallel rings is addressed in chapter 5. We conclude with an outlook on open questions such as the access control protocol and strategies to map different ATM service classes onto paths of different length.

2 ARRAYED WAVEGUIDE GRATING MULTIPLEXER

Traditional WDM networks often use passive star couplers to establish single hop networks. While the advantage of single hop networks over multihop approaches in terms of simplicity and transmission delay is obvious, access control protocols are needed to share the bandwidth of the wavelengths. In most cases a separate signalling channel is used, which turns out to be the bottleneck as the number of wavelengths increases. We propose to use a Arrayed Waveguide Grating Multiplexer instead to interconnect the stations of the network. The device and the possible ring structures on it have been described in [2]. The device can be logically seen as a combination of n demultiplexers and n multiplexers as in figure 1, though it is essentially an analog grating based element with severe limitations in its size due to crosstalk properties. A wavelength on an input of the AWGM appears only on one output. The advantage of such a solution is that this passive device offers n times the bandwidth of a passive star coupler and it is completely collision free. In principle all routing is done by the selection of the input port and the input wavelength. A signal on wavelength $\lambda 1$ from input A in figure 1 is routed to output B‘, while the same wavelength from input B is routed to output C‘ and from input C to output A‘. A station is connected to the AWGM to input X and to output X‘, which both have the same relative distance to the in/output of another station. The output port for a certain signal depends on the distance between the receiver and sender and on the selected wavelength. In other words, to select the channel to a specified station, we have to know the distance of the input ports at the AWGM. We lose one wavelength that is routed back to the originating station, so we have (n-1) usable frequencies, each able to reach exactly one of the (n-1) other stations. The Grating Multiplexer has the nice property of being periodic, that is λx, $\lambda n{+}x$, $\lambda 2n{+}x$... are all being routed to the same output. The number of periods is limited by the higher attenuation of frequencies far away from the center frequency. This feature allows for the use of more than n wavelengths and may actually enable the parallel transmission of more than one bit.

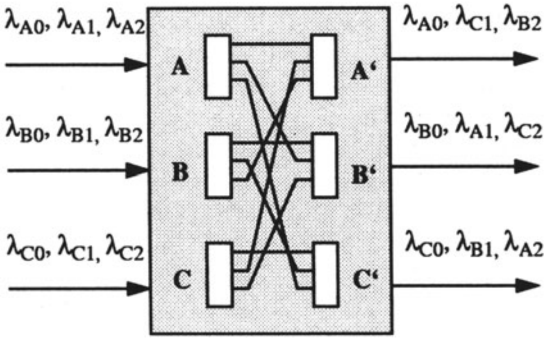

Figure 1 The logical structure of a 3x3 Arrayed Waveguide Grating Multiplexer

3 BASIC NETWORK STRUCTURE

In our architecture we use the AWGM in a physical star topology. The proposed basic network structure is a set of virtual rings on the underlaying physical star topology. In figure 2 a network of 3 stations A, B and C is shown. The two wavelengths form a bidirectional ring structure. This can be seen as a fully meshed configuration, too. A transmission from station A to B may take place not only on the "direct" wavelength $\lambda 1$ but also on $\lambda 2$, when a multihop scheme is introduced and station C works as a relay station for A and B. We see that potentially all of the wavelengths can be used for a transmission between a given pair of stations. Therefore the overall user data rate for an AWGM with n inputs (that is, n stations in maximum) is (n-1) times the bandwidth of a single channel.

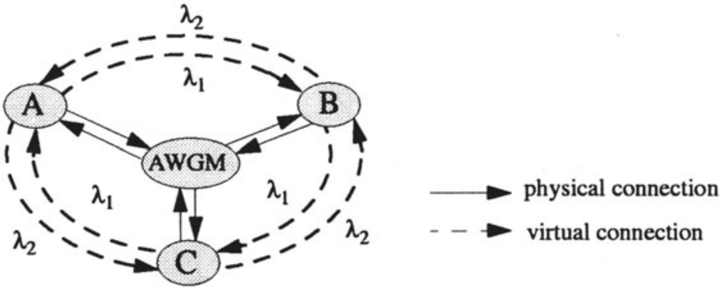

Figure 2 Basic topology of a network made up by a 3x3 AWGM

The routing decision (output wavelength λ) at the sending station is based on:

$$\lambda = (x * n + distance)/m = x * n/m + distance/m \tag{1}$$

for integer numbers m,n and x with:
m = hop number ($1 <= m < n$)
n = number of wavelengths
x = 0...n
distance = distance between receiver and sender at the input

In a case where $m = x * n$, i.e. n is an integer multiple of m, there are wavelengths, which can not be used for transmission to a certain station. This is shown in figure 3, where λ2 makes up two separate rings (A-C and B-D) which are not connected to each other, i.e. they do not share a common station. This feature could be used to set up subnetworks, but in our approach we consider it an unwanted effect. Therefore we conclude that the number of wavelengths n in the network and hence the number of inputs of the AWGM has to be a prime number. With n being a prime number the network consists of (n-1) parallel rings with all stations connected to all rings. We do not consider the periodic nature of the AWGM in the above equation. To take this into account, x would have to go up to 2n, 3n or higher, depending on the number of periods.

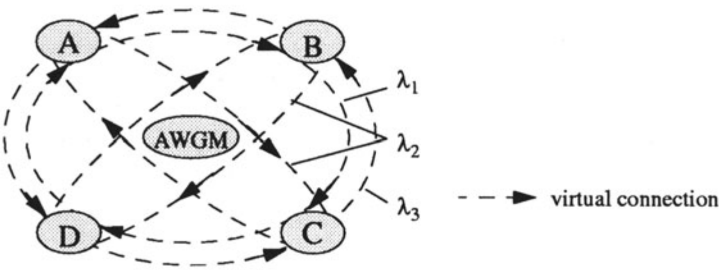

Figure 3 Basic topology of a network made up by a 4x4 AWGM. For better visibility only virtual connections are shown.

4 DESIGN OF THE NETWORK

In general, we do not need to have as many Transmitter/Receiver-pairs as wavelengths in the system. It is possible to start up with only one fixed Tx/Rx pair per station, which results in a unidirectional ring (e.g. only using λ1 in figure 3). By adding additional Tx/Rx pairs we increase the possible throughput of each station. We can thereby scale the available bandwidth between two endpoints to the actual needs. If n is a prime number, the wavelengths λx and λn-x (x=1..(n-1)/2) form counterdirectional rings. If we assume that we send to one out of (n-1) stations in an unidirectional ring structure, each selected with equal probability, the mean transmission delay relates to (n-1)/2. If we now add a second wavelength to form a bidirectional ring, the delay relates

to (n-1)/4. So with an increasing number of wavelengths from 1 to (n-1) we reduce the average hop number from (n-1)/2 down to 1, which is the single hop network.

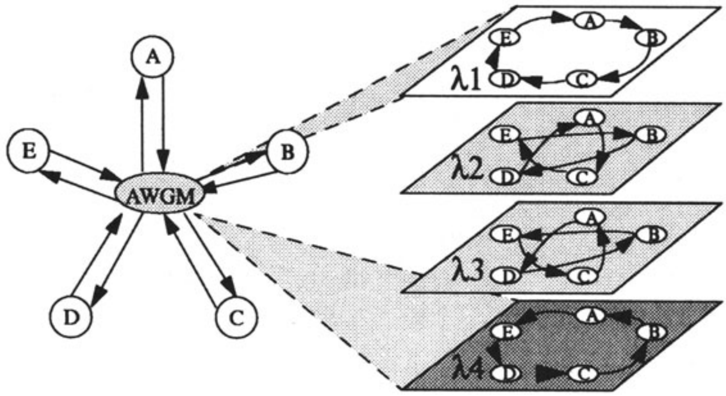

Figure 4 Connections in a network of 5 stations using 4 wavelengths.

There are 3 possible application scenarios for this network: The first possibility is to split the rings up into single point-to-point connections. The second scenario uses SONET/SDH Add-Drop-multiplexers (ADM). A fixed share of the bandwidth is allocated to each connection between two stations. The third and the most flexible approach offers dynamic bandwidth allocation based on a MAC protocol.

4.1 Point-to-Point Connections

The simplest possibility would be to put ATM switches into what is referred to as stations in chapter 3. There would have to be a separate Receiver/Transmitter-pair for each input and output, respectively, each on a separate wavelength. So if we would use only one wavelength, the architecture would essentially look like the distributed ATM switch proposed in [4]. On the other hand, if the network is packet switched, the queueing delay for each packet sums up at each switch between the source and destination of the packet. The routing decision could easily be done by evaluating Equation 1. Incoming packets would be routed to the wavelength with the smallest hop number to the destination. If the shortest path is temporarily unavailable the wavelength with the next higher hop number is selected for transmission. A distinction in the routing decision can be made for different ATM service classes. CBR and VBR traffic should always be routed to the shortest path, whereas ABR traffic might take a longer way to its destination.
The strategy of splitting the rings into point-to-point connections is an easily

applicable way to make use of AWGMs. Still, the bandwidth allocation is not very flexible. For a small number of Transceivers per station the transmission delay of a packet between two stations using the multihop approach could become intolerable.

4.2 Static Bandwidth Allocation

The second approach applies Add-Drop-Multiplexers for each wavelength, as the basic functionality of an Add-Drop-Multiplexer is to be a 2x2 switch. Interestingly, the ideal device to perform demultiplexing and multiplexing on one chip is again the AWGM. A one-chip solution with loop-back optical paths for this is presented in [2]. So the station would employ an AWGM as interface to the optical domain. This increases failure robustness because of its passive nature. It would be possible to have parallel SONET rings with a fixed bandwidth allocation between the stations in a PrimeNet. The station design is shown in figure 5, where the switch on the left can be of any nature. The ADMs are used to either consume the bandwidth or donate it in short cut mode to the other stations.

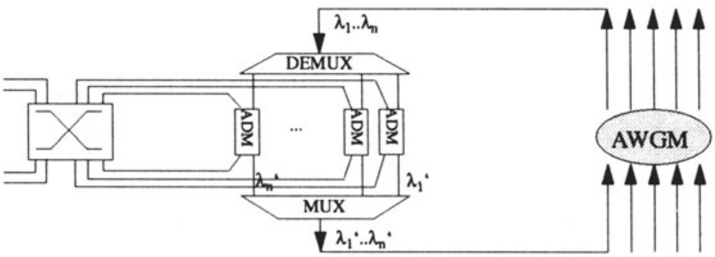

Figure 5 Station design using SONET/SDH rings, λx denotes the input, λx' the output.

4.3 Dynamic Bandwidth Allocation

In order to support the bursty nature of packet switched network traffic bandwidth has to be assigned to stations upon their demand. To achieve this we apply a MAC protocol in between the ADM-stage and the switch or router. Here we may apply well-defined solutions like FDDI, DQDB or CRMA [5], that address the problem of fair bandwidth sharing across a ring or a folded bus. The question which of the existing protocols will be appropriate for the needs of the network remains for further studies. The basic requirements for a Media Access Control Protocol in this architecture are:

- Ability to work equally well for single hop and multihop connections (i.e. independent of the number of rings)
- Low or no reservation overhead in the case of point-to-point connections
- Ability to support QoS - Ability to guarantee bandwidth

The result of the existence of a separate MAC protocol for the network is a new station architecture. It consists of a set of ADMs and a protocol machine to perform routing decisions as well as the actual parallel MAC. A graphical representation for this architecture is shown in figure 6

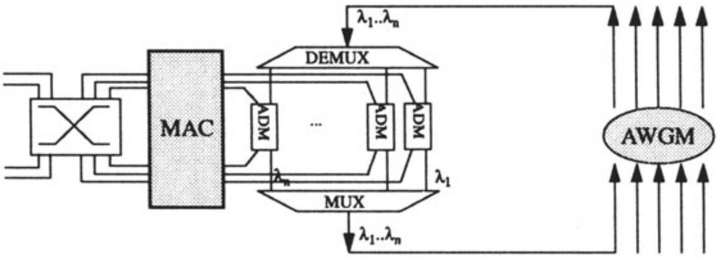

Figure 6 Station design using a parallel MAC machine

5 EXTENDING THE NETWORK/CASCADING AWGMS

So far, we only considered a network with a number of stations equal to the number of inputs of the AWGM. These devices are currently on the market up to a size of 64x64. In order to build networks of, say, 1000 stations or more, we see the need to cascade several AWGMs. A direct connection of AWGMs does not seem to be the proper way because of their modest crosstalk properties. Even if one could employ some kind of signal recovery between the AWGMs, it would physically be the enlargement of every ring on each wavelength involved. So for two networks of 6 stations each (actually 7 stations per network, but one input/output pair is used for the connection to the other AWGM) the direct interconnection of the AWGMs would result in a network of 12 stations on 6 parallel rings, which clearly reduces the available bandwidth for each station. The easiest way to connect two of these networks would be to stick to the point-to-point connections and to have a switch (ATM or IP) which is connected to both. A regular topology which connects every station to two PrimeNets is shown in figure 7. The 16 heptagons represent the PrimeNets that connect the stations. That way we create a robust and redundant topology that eliminates the single point of failure that the AWGM would represent otherwise.

Using this architecture, however, would ask for buffering of data units in the stations. In the case of fixed SONET/SDH bandwidth allocation (chapter

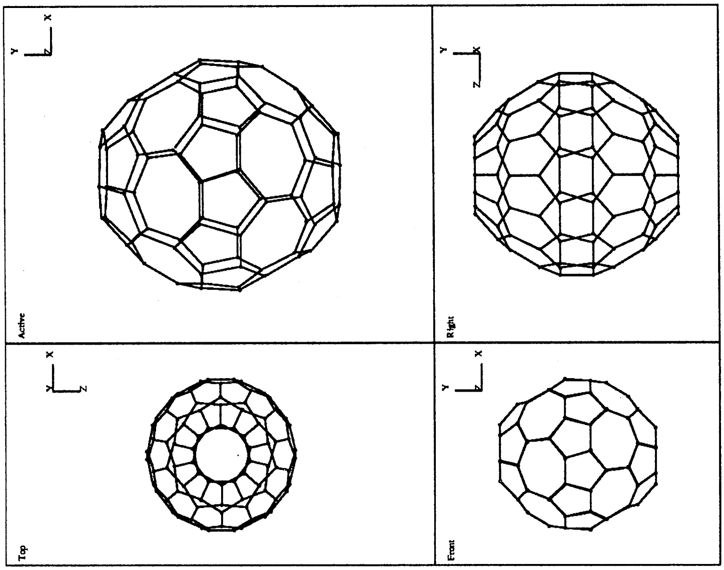

Figure 7 Regular network topology consisting of 16 PrimeNets a 7 switches each

4.2) we would need to have a buffer of at least a SONET/SDH frame size per wavelength to deal with synchronization problems between the two rings. When using the approach of a special parallel MAC protocol, the station connecting the two networks would have to have a second set of ADMs and a second parallel MAC machine. There may be the need for buffering, too, but this depends on the design of the MAC and the reservation policy.

6 CONCLUSIONS

We presented a concept for a backbone network interconnecting a number of high-speed switches or routers based on WDM. The WDM concept is translated into a virtual ring structure on every wavelength. That way we can avoid wavelength conversion within the network. By adding Tx/Rx pairs in the stations we can scale the available bandwidth from 1 to (n-1) times the bandwidth of a single wavelength, possibly even higher due to the periodic nature of the AWGM (Wavelength x, n+x, 2n+x are all routed to the same output). Virtual topologies range from an unidirectional ring to a fully meshed topology. The transmission delay decreases with an increasing number of transceivers per station to the optimum case of a point-to-point connection. We discussed several possibilities for the connections on the rings and proposed for a parallel MAC which allows for a flexible bandwidth allocation. The suitability of existing standards like MetaRing, DQDB or CRMA has to be revisited and is a field for further studies.

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Lightweight Signaling and Efficient Coupling Heuristic for Optical Star Networks MAC Protocols

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Abstract

Several MAC protocols have been proposed to prevent collisions on passive optical star networks. Time Division Multiple Access (TDMA) is a simple way to guarantee conflict-free concurrent transmissions on such networks. Because it does not require any signaling, TDM efficiency is not distance dependant. However, TDM suffers from non negligible access delays under low load. To reduce this drawback, dynamic allocation schemes (DAS) such as the Random Sheduling Algorithm (RSA) or the Group Time Division Multiplexing (GTDM) have been proposed. Both of these mechanisms reserves slots on a packet-by-packet basis by means of a signaling channel. The capacity in bit/s of this signaling channel is directly related to the number of buffers used in each node. The parallel queueing strategy allows to reduce the signaling cost by using a small number of buffers in each node. In that case, coupling algorithms such as the Minimum-degree Vertex First Scheduling (MVFS) have been proposed to manage the packets enqueueing/dequeueing process. In this paper, we propose a new MAC protocol for passive optical star networks which cumulates the benefits of GTDM in terms of lightweight signaling with those of the MVFS algorithm in terms of coupling efficiency. The performance of this new protocol is compared to other existing solutions by means of computer simulations. We also underline the disruptive influence of propagation delays on the DAS-type protocols efficiency.

Keywords : Single-hop networks, passive optical star, MAC protocols, performance evaluation.

Optical Network Design and Modelling H. van As & A. Jukan (Eds.)

1 Introduction

Broadband interactive applications require new network generations for both local area networks (LAN) and long distance networks (WANs). The challenge to satisfy is double : how to offer to each session between such applications a very large bandwidth while maintaining simultaneously a very short network response time. New LANs like Fast Ethernet, 100-VG Any-LAN or FDDI are a first but a limited step in that direction. Three new approaches partially answer this challenge in the field of local area networks. In the the short term, Gigabit-LANs and ATM-LANs look like possible solutions. Like classical LANs, Gigabit-LANs are based on a broadcasting medium. Metaring [1], ATM-Ring [3] or CRMA-2 [2] are some examples of Gigabit-LANs. These networks allow a significant increase in the medium capacity up to the Gigabit range by means of slot reuse, concurrent transmisions and multiple path routing. Unlike Gigabit-LANs of which capacity is given by the medium bandwidth, ATM-LANs offer a better scalability. Indeed, a load increase on an ATM-LAN may be satisfied by adding new switches and new links. Nevertheless, Gigabit-LANs and ATM-LANs are limited in terms of bandwidth and of response time because of the electro-optic bottleneck. For both of them, the speed of electronics must be of the same order of magnitude as the aggregate throughput on each link. Wavelength Division Multiplexing (WDM) is a very promising alternative to overtake this limitation in bandwidth. Instead of using a single channel per link with a high bit rate, WDM allows to create several optical channels of a few Gigabit/s on a same fiber. A specific wavelength is associated to each of these channels between a sender and a receiver. The speed of electronics in an end-station is then given by the speed of a single optical channel. In high speed networks, propagation delay is predominant over transmission delay[1]. For a given optical link between two nodes, network reponse time is given by the summation of the cumulated propagation delay T_p and of the cumulated nodes latency T_l. If it is not possible to improve T_p, a reduction in T_l may be obtained by replacing active connections by passive ones. Passive optical connections guarantee a null station latency. On the other hand, fast tunable transmitters/receivers facilitate a dynamic allocation of wavelengths among the various couples sender/receiver. Single-hop all-optical LANs turn to good account of all these improvements.

Several topologies have been investigated for single-hop all-optical LANs. In this paper, one considers the case of passive optical star coupler networks. One assumes that stations use fixed transmitters and tunable receivers. Contentions may occur if two users want to communicate simultaneously with a same destination. Different medium access protocols (MAC) have been proposed for conflict-free access to passive optical star networks. Most of them use a synchronization between nodes allowing a slotted access. Preassigned wavelentgth allocation based on a Time Division Multiple Access scheme is the simplest way to prevent any contention on passive optical star networks. Such a MAC protocol does not optimize access delays in case of low loads. To reduce this drawback, Dymamic Allocation Schemes (DAS) have been proposed in the litterature. In each station i, generated packets are stored in distinct buffers according

[1] This duality is called delay×bandwidth product.

to their destination address. The state of the network at each instant is given by the amount of packets in these buffers. Dynamic allocation schemes assume that at the beginning of each slot, each station has a partial knowledge of the state of these queues. A signaling channel must be used for that purpose. In section 2, we recall the main characteristics of passive optical star networks. We describe the principle and underline the limits of the TDM access. In section 3, two dynamic allocation schemes (DAS) are presented : the Random Sheduling Algorithm (RSA) and the Group Time Division Multiplexing (GTDM). Both of these schemes reserve slots on a packet-by-packet basis. The cost in bits of the signaling channel for such dynamic schemes strongly limits the amount of nodes that may be connected to the network. New buffering strategies have been investigated to solve this problem. The Parallel Queueing technique which is one of them is presented in section 4. Some algorithms such as the Minimum-degree Vertex First Scheduling (MVFS) must be associated to parallel queueing for managing the enqueueing and the dequeueing of the various buffers in each node. In section 5, we show that the MVFS allows a much better coupling efficiency between nodes than the RSA. We then propose a new MAC protocol for passive optical star networks which cumulates the advantages of GTDM in terms of signaling cost and of the MVFS in terms of coupling efficiency. Several simulation results are presented and commented to compare the performance of the GTDM+MVFS scheme with other existing protocols. Finally, we conclude this paper in section 6 by underlining the disruptive influence of propagation delays on the performance of DAS-type protocols.

2 Passive optical star networks with TDM access

2.1 Configuration

In single-hop all-optical networks, a source node is connected with a destination node by means of an end-to-end optical channel. Passive folded bus and passive optical star are two possible topologies for single-hop all-optical networks. Both of these topologies uses 2×1 and 1×2 passive optical couplers. Figure 1 illustrates a passive optical star configuration with $N = 4$ stations.

Unlike folded bus topology, optical-star topology allows a fixed and low attenuation between any couple source/destination. Each wavelength λ_i associated to a transmitter i is broadcast toward all the stations of the network. Let P be the optical power of a transmitter. Let α and β be respectively the attenuation of 2×1 and 1×2 couplers. Any receiver detects optical signals with a power $\alpha^2.P.\beta^2$. Let j be the index of the destination node of a packet sent by node i. By means of a tunable receiver, node j is able to select the wavelength λi among the composite spectrum it receives. One assumes here that the receiver is informed by the transmitter of the tuning wavelength. Either this information is given before each packet transmission (optical packet switching), or before the opening of a communication (optical circuit switching). Because receivers can only tune to a single wavelength at a given instant, contention may occur if several stations try to transmit simultaneously to the same receiver.

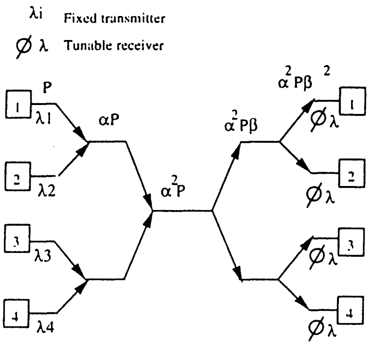

Figure 1: Principle of the passive optical star coupler network.

2.2 The Preassigned Time Division Multiplexing (TDM)

Time division multiplexing is the simplest way to prevent any collision on a passive optical star. The N stations of the network are synchronized. Time is slotted in fixed intervals which impose a common packet size. For sake of simplicity, we assume that a station may send packets to itself. The packets generated by each node i are stored in N separated queues according to their destination address. Let Δ be the slot duration. A frame structure composed of N slots is simultaneously broadcasted to the each station. Figure 2 illustrates the principle of preassigned TDM access. At instant t_1, which is the beginning of the first slot of a frame, stations 1, 2, ... N are respectively allowed to transmit a packet to stations 1, N, $N-1$,...2. Using a cicular permutation in the sucessive slots assignment, one may notice that each station is allowed to send at most one packet per frame to any receiver. TDM access is well suited for optical circuit switching. Because it does not require any signaling, TDM access is insensitive to distance. The price of this simplicity is paid by non negligible access delays under low loads.

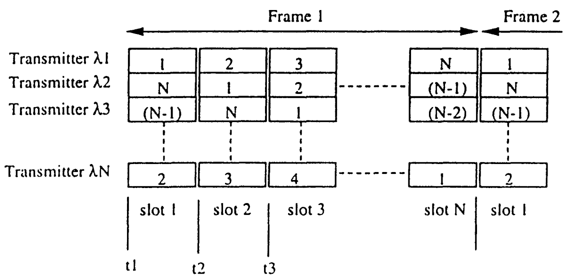

Figure 2: Principle of the TDM access on a passive optical star network.

3 Dynamic Allocation Schemes (DAS)

Let us assume that time is slotted and that stations are synchronized. Optical packet switching requires that wavelength allocation is made on a packet-by-packet basis. In that case, a signaling channel is mandatory to inform during each slot k on which wavelength each receiver will have to tune a few slots later. To prevent any collision, each node of the network must have, slot by slot, a partial knowledge of the state of the buffers of the $N-1$ other nodes. On the basis of this knowledge, all the stations run a common algorithm to decide on which received wavelength they have to tune. Two main problems appear in that case. First, the amount of necessary bits to broadcast slot by slot the information relative to the state of the buffers is limited because of the finite capacity of the signaling channel. Secondly, the shorter the slot duration, the more influent the propagation delays of signaling information on data packet access delays. Let us consider for instance a packet size equivalent to the payload of an ATM cell (48 bytes). If each transmitter allows a throughput of 1 Gbit/s, a slot duration is then 384 ns. Assuming a signal velocity $\mathcal{V}$ on the optical fibre of 180.000 Km/s, distance between a sender and a receiver must be less than 70 meters. Thus, knowing the state of the buffers at the beginning of slot k, stations are authorized to transmit at the beginning of slot $k+1$ only in the case of very short range networks. One assumes in the following the use of an out-of-band signaling. In addition to its fixed transmitter on wavelength λ_i, each station i owns another fixed transmitter on a common wavelength λ_s. Likewise, in addition to its tunable receiver, each node i owns a fixed receiver on the wavelength λ_s. Concurrent transmissions on this common signaling channel are made on the basis of a TDM access.

3.1 The Random Scheduling Algorithm (RSA)

The Random Scheduling Algorithm (RSA) has been proposed in [4] for wavelength allocation in dynamic allocation schemes. The RSA is based on a same random number generator seed implemented in each station of the network. As soon as they have received the information about the state of the buffers, all the stations run the RSA and mutually arrive to the same conclusion. Effective transmissions may occur at the best when the most distant sender and receiver have in their turn arrived to this same conclusion. The RSA is run at the beginning of every slot. Figure 3 gives an example of the buffers state between two successive slots in the case of a network with $N=3$ stations. Let i be the index of the transmitters and j be the index of the queue containing packets for node j. We assume that the slot duration on the signaling channel is identical and synchronized with the slot duration Δ on the data channels.

Figure 4 describes the principle of the out-of-band signaling channel associated to the RSA. We see on this figure the information sent on the signaling wavelength λ_s by the N stations while they are in the state given by Figure 3. A slot duration on the signaling channel is devided in N minislots. Each minislot is itself devided in N bits. By convention, the i-th minislot of each frame is dedicated to station i. The j-th bit in the i-th minislot is set to "1" if station i has at least one packet waiting for

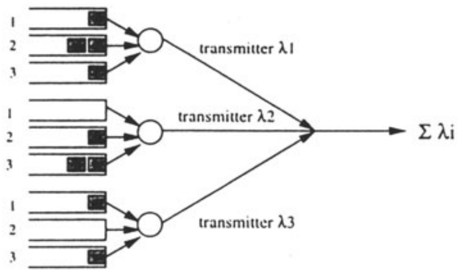

Figure 3: A possible state for the different queues of a network with 3 nodes.

transmission in its queue j. If it is not the case, this bit remains to "0".

We see from Figure 4 the influence of signaling propagation delays on data packet access delays. Let Ω be the set $\{1, 2, ..., N\}$. The Random Scheduling Algorithm is then :

1. A transmitter i_1 is randomly selected in Ω.
2. A queue j_1 is randomly selected among the nonempty queues of station i_1 ($j_1 \in \Omega$). At the end of the RSA execution, station i_1 will be allowed to send a data packet towards station j_1.
3. A second transmitter i_2 with $i_2 \neq i_1$ is randomly selected among Ω.
4. A queue j_2 with $j_2 \neq j_1$ is randomly selected among the nonempty queues of station i_2 ($j_2 \in \Omega$). At the end of the RSA execution, station i_2 will be allowed to send a data packet towards station j_2.
5. Steps 3 and 4 are repeated, each time by removing from $\Omega \times \Omega$ a new couple (i_x, j_x), until all the N stations have been considered.

Figure 5 illustrates by means of a bipartite graph the state of the queues corresponding to Figure 3. The left part and the right part of the graph respectively corresponds to the transmitting side and to the receiving side. For each node i, vertex E_i corresponds to the fixed transmitter and vertex R_i corresponds to the tunable receiver. An edge exists from vertex E_i to vertex R_j if there is at least one packet in station i waiting to be transmitted towards station j.

Let us consider for instance a possible sequence α given by the RSA. This sequence α is illustrated by the bipartite graph given in Figure 6 :

$$\alpha = \{(i_1 = 1, j_1 = 2), (i_2 = 3, j_2 = 1), (i_3 = 2, j_3 = 3)\}$$

The RSA presents two major drawbacks. The cost in bit of the signaling information increases in N^2. These N^2 bits must be sent during a slot duration Δ. If the signaling channel and the data channels have the same capacity in bit/s and if L stands for the

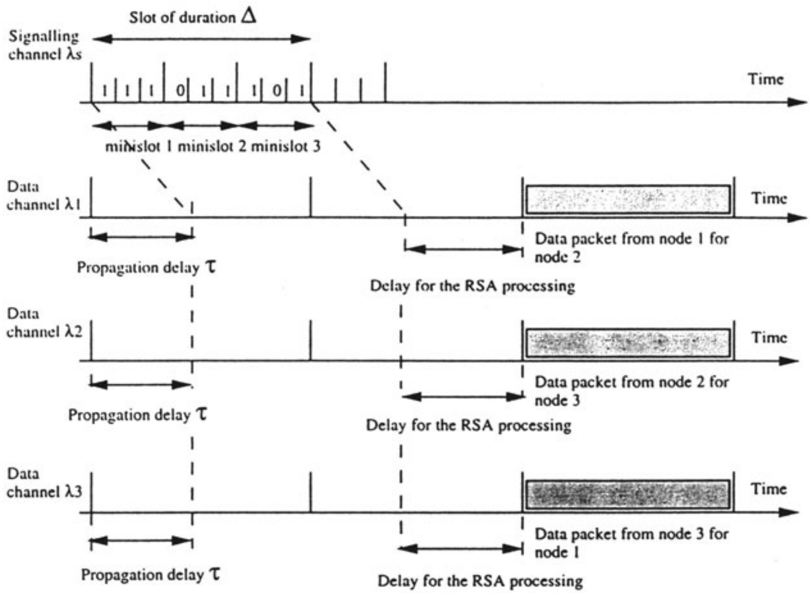

Figure 4: Time structure of the signaling channel and of the data channels of the RSA.

packet size in bits, the maximum number N_{max} of nodes that may be connected to the network is :

$$N_{max} = \lfloor \sqrt{L} \rfloor \tag{1}$$

If $L = 48$ bytes, then only up to 19 stations may be connected to the network. The non-optimal coupling between transmitters and receivers is the second drawback of the RSA. Figure 7 gives the bipartite graph associated to another possible random sequence α' :

$$\alpha' = \{(i_1 = 1, j_1 = 2), (i_2 = 3, j_2 = 3), (i_3 = 2, j_3 = ?)\}$$

The sequence α' induces a waste in bandwitdth utilization because station 2 is not allowed to transmit.

3.2 The Group Time Division Multiplexing (GTDM)

Several algorithms have been proposed in the litterature so as to offer a better coupling efficiency than the RSA. The Hybrid Time Division Multiplexing (HTDM) is a combination of TDM and RSA [4]. The HTDM uses a frame divided in $N + M$ slots, where N still stands for the number of nodes on the network. Globally, stations access the

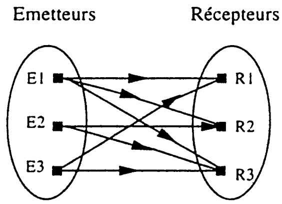

Figure 5: Bipartite graph associated to state of the different queues.

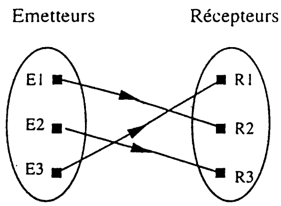

Figure 6: Bipartite graph associated to the random sequence α.

networks by means of preassigned slots (N preassigned slots per frame). After every N/M slots (with $N \geq M$ and M is an integer), an "open" slot authorizes a station to transmit a packet to any receiver. To prevent contentions, open slots are allocated by means of the RSA. The HTDM reduces the cost of the signaling channel in comparison to the pure RSA. Indeed, the N^2 bits necessary to describe the state of the N^2 queues are transmitted during N/M slots instead of one slot for the pure RSA. For a packet size L, the signaling cost limits the number N_{max} of stations that may be connected to the network such as :

$$N_{max} = \lfloor \frac{L}{M} \rfloor \tag{2}$$

If $L = 48$ bytes, several values of the couple (N_{max}, M) are possible : (192, 2), (96, 4), (48, 8), (32, 12).

The Group Time Division Multiplexing (GTDM) is also based on a combination of TDM and RSA [6]. The set of N nodes is divided in several groups g_m with $m \in \{1, 2, ..., K\}$ and $K \leq N$. Stations of group g_m may communicate with stations of group g_n during preassigned periods of time. Figure 8 illustrates the principle of GTDM. Again, stations are synchronized and time is slotted. A frame is devided into K slots. At instant t_1, transmitters of group g_1 can send packets only to receivers of the same group, transmitters of group g_2 can send packets only to receivers of group g_K and so on. A circular permutation in the successive slots assignment allows to prevent from any optical contention between the different groups. During each preassigned slot, the RSA is applied inside each group to determine the transmitter/receiver pairs for the

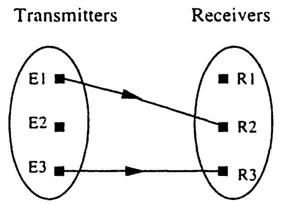

Figure 7: Bipartite graph associated to the random sequence α'.

next slot. The signaling cost of GTDM is sensibly reduced compared to RSA. Instead of sending N bits per slot as with RSA, a station only sends N/K bits per slot with GTDM. If L is the data packet size, the signaling cost limits the number of stations that may be connected to the network to N_{max} such as :

$$N_{max} = \lfloor \sqrt{K.L} \rfloor \tag{3}$$

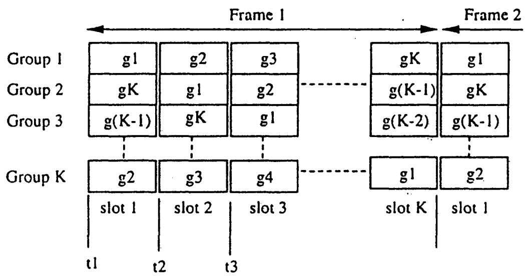

Figure 8: Principle of the Group TDM access on a passive optical star network

If $L = 48$ bytes and $K = 4$, $N_{max} = 38$ which is twice the capacity given by pure RSA. In the case of symmetrical traffic, the groups are of the same size N/K (if N is even). In the case of asymmetrical traffic, the choice of the groups aims to minimize the contention probability. Thus, two stations generating many packets for a same destination should be placed in distinct groups.

4 The Parallel Queue Scheduling

The access protocols decribed above assume that in each node, generated packets are stored in different queues according to their destination address. The Parallel Queue scheduling proposed in [5] allows to use a reduced number of queues in each node by means of a two stage buffering. Like GTDM and RSA, parallel queue scheduling assumes a synchronization of the stations and a slotted access. An out-of-band signaling

channel is also shared by the N stations by means of a TDM access. This signaling channel uses a specific wavelength λ_s. Figure 9 describes the configuration of a station with Parallel Queue scheduling.

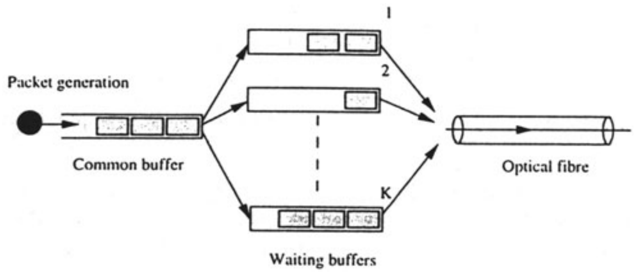

Figure 9: Principle of the Parallel Queue Scheduling.

The first stage is made of a large size FIFO buffer. The second stage is divided in K parallel buffers (waiting buffers) with a same capacity S. The value of K is fixed and low (5 or 6) for any network configuration. In each station i, generated packets are first of all stored in a the common FIFO buffer. At the beginning of each slot, the packet located at the head of the common buffer is enqueued in one of the waiting buffers. Two policies are proposed for the choice of the parallel buffer :

- **Policy 1:** The set of the N receivers is divided into K groups. A parallel queue is thus associated to a given set of destination adresses.
- **Policy 2:** The least loaded parallel queue is systematically chosen.

For both policies, a station broadcasts on the signaling channel the destination address of a packet as soon as this one has been transfered from the common buffer to one of the parallel queues. If policy 2 is adopted, a station also broadcasts the index of the chosen parallel queue. Thus, any station of the network knows slot by slot the state of the K parallel queues of the $N-1$ other stations. This knowledge is then used to determine the transmitter/receiver pairs. Let Δ be the slot duration and τ be the propagation delay. A station is not allowed to send a packet before the corresponding signaling message has arrived to all the receivers. In other terms, this packet have to be buffered in a parallel queue at least during a delay τ. The minimum size S of the parallel queues is then given by :

$$S = \lceil \frac{\tau}{\Delta} \rceil$$

The cost of the signaling channel is given by the number of bits to be sent during each slot duration. In the case of policy 1, one assumes that an address "0" corresponds to an empty common buffer. The signaling cost is then $N.\log_2(N+1)$. In the case of policy 2, $\log_2 K$ bits are necessary to identify in a given node the used parallel queue.

The signaling cost is then $N.\log_2(N+1) + N.\log_2 K$. If L is the data packet size, the signaling cost limits the number N_{max} of stations that may be connected to the network. In the case of policy 1, one has :

$$N_{max}.\log_2(N_{max}+1) \leq L \tag{4}$$

If $L = 48$ bytes, then $N_{max} = 63$. In the case of policy 2, the value of N_{max} is given by :

$$N_{max}.\log_2 K.(N_{max}+1) \leq L \tag{5}$$

After all the stations have been informed of the presence or of the absence of a packet in the parallel queues, a simple heuristic algorithm given in [5] determines the transmitter/receivers pairs. This heuristic called the Minimum-degree Vertex First Scheduling (MVFS) is described below. Let us consider the bipartite graph including the set T of the transmitters (left part of the graph with vertices E_i) and of the set R of the receivers (right part of the graph with vertices R_j). At most K edges link a vertex E_i to K vertices R_j. The different steps of the MVFS are the following ones :

1. Sort the vertices of R according to the increasing order of the number of edges arriving on each of them.
2. Select randomly one vertex R_{j1} among those with the lowest order.
3. Select randomly one vertex E_{i1} among those linked to R_{j1} with an edge.
4. Remove E_{i1}, R_{j1} and all the edges originated from E_{i1} and all the edges arriving at R_{j1} .
5. Repeat steps 1 to 4 until all the stations have been consulted.

5 The GTDM+MVFS scheme : a new access protocol

5.1 The MVFS coupling efficiency

We propose to associate the MVFS heuristic with the GTDM so as to cumulate the benefits of each of these mechanisms. Compared to pure RSA, GTDM allows a lightweight signaling. The higher the number of groups, the lighter the signaling cost and the larger the number of nodes that may be connected to the network. MVFS is much more efficient in terms of coupling efficiency than RSA. Let us consider the very simple case of a 2 nodes network. Figure 10 illustrates network state at the beginning of a given slot. With RSA, the probability to choose E_1 at the first step of the algorithm is 0.5. The probability to choose R_2 at the second step is 0.5. In that case, one may notice that vertex E_2 cannot be selected for the next transmission. In other words, the average coupling given by RSA is 1.75. With MVFS, the first vertex to be selected is R_1. Then E_1 is selected. After having removed E_1, R_1 and the associated edge, R_2 and E_2 are

always selected for the next transmission. As a conclusion, the MVFS allows for this simple example an average coupling of 2 instead of 1.75 with the RSA. We shall see in the following section, that this improvement is not negligible in terms of access delay for moderate to high loads.

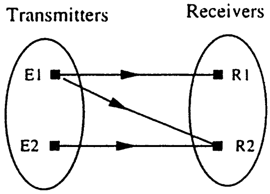

Figure 10: A comparison between the MVFS scheduling and the RSA scheduling.

5.2 Performance analysis

In all our simulations, stations are assumed equidistant. Propagation delay on the signaling channel is neglected. Each station i generates packets during a slot according to a Bernoulli process. Let p be the probability that station i generates a packet during a slot. Let $p_{i,j}$ be the probability that station i generates a packet for station j during a slot :

$$p = \sum_{j=1}^{N} p_{i,j} \leq 1 \qquad (6)$$

One assumes in all our simulations that the N stations of the network generate a same traffic load ρ. This offered load is thus given by probability p. In the following, G stands for the number of groups. For each simulation result, the vertical axis corresponds to the mean packet access delay expressed in slot durations. The horizontal axis corresponds to the offered load p. Several access protocols are compared: TDM, pure RSA ($G = 1$), pure MVFS ($G = 1$), GTDM+RSA and GTDM+MVFS.

5.2.1 Behaviour under symmetrical traffic

Let us consider a passive optical star network with $N = 8$ nodes. A packet generated by station i has the same probability to be enqueued in any queue j, that is $p_{i,j} = p/N, \forall j \in \{1, 2, ..., N\}$. The groups are chosen of the same size. Mean packet access delay $E[d_{i,j}]$ for the TDM scheme has been derived in [7]:

$$E[d_{i,j}] = 1 + \frac{(N-1)}{2(1 - N.p_{i,j})} \qquad (7)$$

In the case of symmetrical traffic, one has:

$$E[d] = 1 + \frac{(N-1)}{2(1-p)} \tag{8}$$

Figure 11 describes by means of a semi-logarithmic scale the evolution of mean packet access delay versus offered load. Under low load, the TDM scheme presents the highest access delays, around 4.5 slot durations, in coherence with the above analytical expression. Mean access delay $E[d]$ for pure RSA ($G = 1$) has been derived in [4] in the case of symmetrical traffic:

$$E[d] = \frac{(1 - p/N)}{(1-p)} \tag{9}$$

As mentionned in [4], we confirm that this analytical result is very accurate for any load. For instance, under low load, E[d] = 1, for a load of 0.8, E[d] = 4.5. The gap between the curve of TDM with the curves relative to dynamic allocation schemes increases with the offered load. Pure RSA and pure MVFS offers respectively better access delays than hybrid schemes like GTDM+RSA and GTDM+MVFS in the case of 2 groups ($G = 2$). One notices that over a 50% load, GTDM+MVFS offers lower access delays than GTDM+RSA. This improvement of about 50 % under high loads. Larger number of groups are considered in Figure 12. For both GTDM+RSA and GTDM+MVFS, the larger G, the longer access delays. This result is quite intuitive. If the number of groups G tends towards N, both GTDM+RSA and GTDM+MVFS behave like the TDM scheme. On the other hand, the larger G, the greater the gain in the signaling cost. The choice of G is then the result of a compromise.

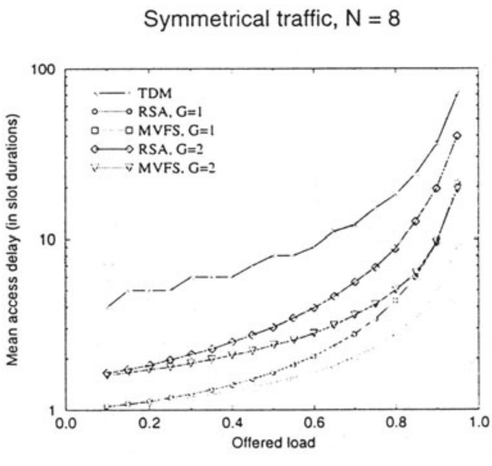

Figure 11: Mean access delay versus offered load, $G = 1$ or 2, $N = 8$.

An analytical expression of mean access delay has been derived in [6] for GTDM+RSA in the case of symmetrical traffic:

$$E[d] = \frac{(1 - p/N)}{(q - p/N)} + \frac{(G-1)q\{(2-q)p/N - (p/N)^2\}}{2p/N(q - p/N)(q - Gp/N)} \tag{10}$$

If k stands for the number of stations in a group ($G = N/k$), the parameter q is approximatively given by:

$$q = \{1 - \frac{(k-1)p}{k}\} \tag{11}$$

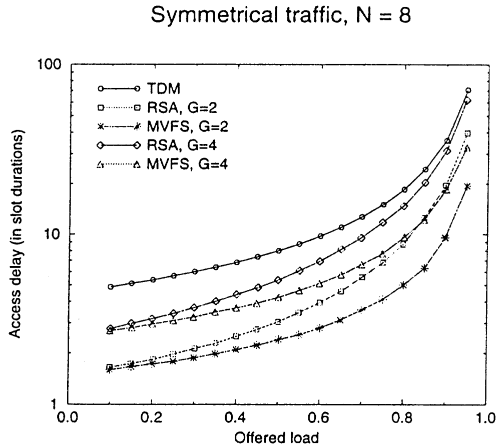

Figure 12: Mean access delay versus offered load, $G = 2$ or 4, $N = 8$.

One notices that if $k = N$, the first term in the expression of E[d] corresponds to the average access delay of pure RSA. Under low load, Figure 12 confirms the above analytical expression of E[d]. Indeed, one has:

$$\lim_{p \to 0} E[d] = 1 + \frac{(G-1)}{2} \tag{12}$$

Thus, in the case of $G = 2$, E[d] tends towards 1.5, and in the case of $G = 4$, E[d] tends towards 2.4. Figures 13 and 14 considers the case of a network with $N = 20$ stations and respectively a number of groups $G = 1$ or 2 (Figure 13), and $G = 4$ or 10 (Figure 14).

Under low load, one notices that, as expected, the larger N, the longer access delays for TDM. Equation (8) shows that E[d] tends to $N/2$ when N is getting very large. We underline here the main drawback of TDM. Pure RSA, pure MVFS, GTDM+RSA and GTDM+MVFS keep roughly the same access delays under low loads when N increases.

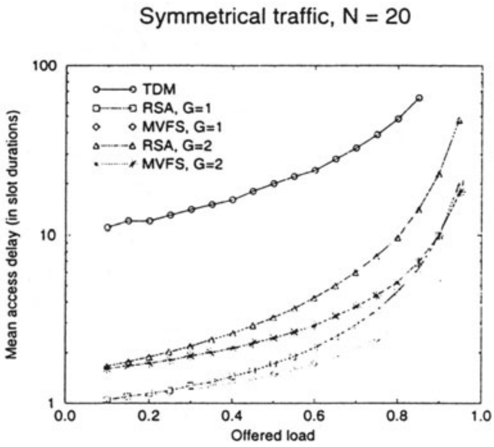

Figure 13: Mean access delay versus offered load, $G = 1$ or 2, $N = 20$.

The GTDM+MVFS offers in any configuration the lowest access delays. The number of groups G may be chosen according to the number of nodes connected to the network.

5.2.2 Behaviour under asymmetrical traffic

We consider now the case of an asymmetrical traffic on a passive optical star with $N = 8$ nodes. Propagation delay is still neglected. The traffic matrix P is such as :

$$P = \begin{pmatrix} 0.01 & 0.01 & 0.01 & 0.01 & p & p & p & p \\ 0.01 & 0.01 & 0.01 & 0.01 & p & p & p & p \\ 0.01 & 0.01 & 0.01 & 0.01 & p & p & p & p \\ 0.01 & 0.01 & 0.01 & 0.01 & p & p & p & p \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.01 & 0.01 & 0.01 & 0.01 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.01 & 0.01 & 0.01 & 0.01 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.01 & 0.01 & 0.01 & 0.01 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.01 & 0.01 & 0.01 & 0.01 \end{pmatrix} \tag{13}$$

Each component $p_{i,j}$ of the matrix is such that i stands for the transmitter address and j stands dor the receiver address. The set of nodes $\{5, 6, 7, 8\}$ generate a fixed traffic which is in big part intended for nodes 1, 2, 3 and 4. The set of nodes $\{1, 2, 3, 4\}$ generate a fixed and low traffic intended for nodes belonging to the same set. This same set of nodes globally generate a variable traffic with intensity $4p$ equally intended for nodes 5, 6, 7 and 8. In our simulations, $4p$ fluctuates from 0 to 0.96. In the case $G = 2$, we have determined randomly which nodes belong to each group. In Figure 15,

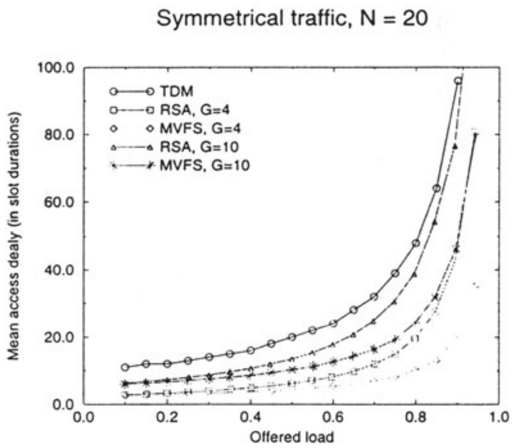

Figure 14: Mean access delay versus offered load , $G = 4$ or 10, $N = 20$.

one has plotted mean access delays versus p for the queue $j = 5$ of node $i = 1$. Using equation (7), we check the validity of TDM access delays under asymmetrical traffic. If $p_{1,5} = p = 0.05$, $\mathrm{E}[d_{1,5}] = 6.8$. When $p_{1,5}$ tends to 0.125 (that is 1/8), $\mathrm{E}[d_{1,5}]$ tends to infinity. Again, pure MVFS gives the lowest access delays and GTDM+MVFS offers lower access delays than pure RSA for loads over 0.2.

The best choice for the groups consists in separating the nodes generating a high load for the same destinations. One reduces like this the conflict probability. In the case of $G = 4$ (which has not been simulated), the following groups should allow the best performance: $g_1 = \{1, 5\}$, $g_2 = \{2, 6\}$, $g_3 = \{3, 7\}$, $g_4 = \{4, 8\}$.

6 Influence of propagation delays

We underline in this section the disruptive effect that may result from propagation delay τ on the DAS-type protocols performance. Several papers assume that access delays with non-zero propagation time may be simply deducted from access delays with zero propagation time by adding the constant factor τ. Let us consider the example described in Figure 16. This figure represents the evolution of the state of a buffer in a given node connected on a passive optical star network. One assumes a propagation delay τ of 4 slot durations. The observed station generates a packet every 2τ. For the sake of simplicity, one assumes that the RSA always authorizes this station to dequeue a packet from the considered buffer. A first packet is generated at instant t_1. Simultaneously, the station sends an information in a minislot on the signaling channel to inform other stations. The RSA algorithm is activated only at instant t_5, just after

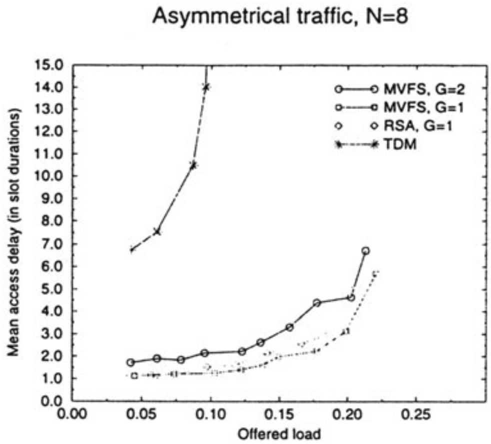

Figure 15: Mean access delay versus offered load, $G = 1$ or 2, $N = 8$.

the minislot has been received by the other nodes of the network. We assume in our example that the RSA processing time is negligible. The observed station is allowed to transmit its packet at instant t_5. Several remarks may then be done:

- The packet generated at t_1 is transmitted 4 slots later at t_5.
- Because it cannot anticipate on the result of the RSA, the station continues to send a bit "1" on the same minislot of the signaling channel until instant t_5.
- Slots beginning at t_6, t_7 and t_8 are reserved by mistake.
- At instant t_9, a second packet is generated. This packet cannot benefit of the 3 "useless" previous signaling bits.
- If a packet had been generated at instant t_6 or t_7 or t_8, it should have benefit of a "useless" reserved slot. Its access delay should have been null, whereas the first packet access delay is 4.

Thus, in the case of a periodic traffic where a packet is sent every 2 τ, the RSA reverves 50% of the bandwidth instead of one slot every 2τ. The larger τ, the least efficient the RSA. The parallel queueing does not suffer from the same inefficiency.

7 Conclusion

Passive optical star coupler networks are a very promising alternative in the field of Gigabit/s Local Area Networks. Optical packet switching requires dynamic wavelength

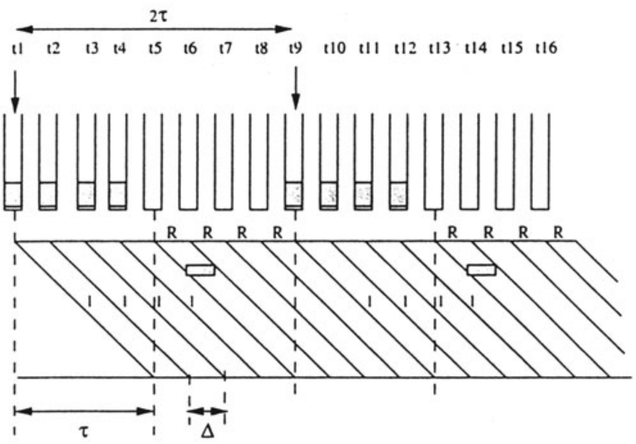

Figure 16: Behaviour anomaly of RSA scheduling due to propagation delay.

allocation schemes. Such schemes are sensitive to contentions. Conflict-free access is obtained by means of a signaling channel allowing each station to have a partial knowledge of the network load. In this paper, we have proposed a new MAC protocol which cumulates the benefits of the Group Time Division Multiplexing (GTDM) with those of the Minimum-degree Vertex First Scheduling (MVFS). GTDM allows a lightweight signaling. By this fact, a larger number of nodes may be connected to the network. We have underlined the fact that the MVFS offers a better coupling efficiency than the Random Scheduling Algorithm (RSA). The new proposed protocol (GTDM+MVFS) has been compared by computer simulations with other existing protocols such as TDM, pure RSA and GTDM+RSA . Pure MVFS allows the lowest access delays for moderate to high loads. In the case of symmetrical traffic, for loads greater than 50% and for a given number of groups, GTDM+MVFS offers better performance than GTDM+RSA. We have underlined the disruptive influence that propagation delays may have on DAS-type protocols. Under high loads, GTDM+MVFS offers better access delays and a lighter signaling cost than GTDM+RSA. The same conclusion has been obtainded in the case of asymmetrical traffic conditions. In a coming paper, we shall propose a new slot reservation mechanism for the GTDM+MVFS able to reduce this drawback.

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PART FOUR

Network availability and performance modelling

RESTORATION AND SPARE CAPACITY ASSIGNMENT IN WDM NETWORKS

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technical subject area:
designing WDM networks for reliability and availability.

keywords:
spare capacity planning + strategies for network restoration, optimisation techniques (integer linear programming)

Extended abstract

WDM technology is an emerging technology to enhance the capacity of the existing fiber plant. The throughput is in the order of tens or hundreds of Gbit/s, even in the order of Tbit/s [1,2]. This urges on finding adequate and cost effective means to survive failures in the network. In this paper restoration techniques in WDM networks are discussed and their spare capacity requirement is compared.

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Optical Network Design and Modelling H. van As & A. Jukan (Eds.)

Only single link failures are considered as in large scale networks a cable break or line system failure is supposed to happen more likely than a node failure. Besides in a node vital parts can be protected by duplicating some equipment. Note that a line system termination is physically located in a node, but its failure affects the link and does not affect the node!

Three restoration strategies are considered: link restoration, path restoration and path restoration with link-disjunct route (or the last one also called backup path restoration). Restoration is understood as rerouting through a reconfiguration of crossconnects. In WDM networks we distinguish wavelength routing networks and wavelength translating networks. In wavelength translating networks the crossconnects are equipped with wavelength converters and therefore there is no constraint on the wavelengths used by the restoration route. The signal may be routed on different wavelengths in the sequential links of the route. In wavelength routing networks however, there are wavelength constraints on the restoration routes. In case of link restoration only the channel in the interrupted link which might be part of a route, is rerouted and must therefore be rerouted on the same wavelength as the rest of the path.

In case of path restoration the transmitters can be tunable or spare transmitters on other wavelengths are available. In that case a route on another wavelength is allowed for rerouting, otherwise a route on the original wavelength must be found. It is clear that the same wavelength must be available along the entire route as there is no possibility of wavelength conversion in the intermediate nodes.

To be able to reroute, spare capacity must be assigned in the network. This spare capacity assignment for each of these strategies is performed by using Integer Linear Programming (ILP) [3,4]. The problem is therefore expressed in a linear model. Linear Programming (LP) finds a lower bound for the specified problem and

an interrupted branch and bound process returns an integer solution which is a rounded solution of the LP-solution.

In terms of spare capacity requirement, link restoration is most expensive, but when implemented as restoration technique in a network, it allows a fast rerouting upon a failure. Path restoration is cheaper but the restoration process takes longer as the interrupted paths upon a failure are rerouted separately. Releasing capacity of interrupted paths on intact links allows capacity reuse on this links and therefore less spare capacity to be fully restorable. However, the drawback is that it requires more reconfiguration actions in the network.

The third studied restoration technique, path restoration with link-disjunct route, uses for each path one restoration route that can be used in case of a breakdown of the working path due to any link failure. By optimising the choice of the restoration route per path, this technique requires less spare capacity than link restoration and only slightly more than path restoration. However, it is simpler to implement than path restoration as only one restoration route must be stored for each path.

The remarks above hold for wavelength translating networks. It is expected that they do as well for wavelength routing networks. The benefit of wavelength conversion for static routing was already found to be low [5]. For the spare capacity assignment and rerouting problem first results show that we can expect to come to the same conclusion.

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Availability comparison of two all-optical network approaches

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Abstract: *Two all-optical network approaches, the partitioned and grid connect, are compared from the availability point of view. The availability measures are defined. The availability model and calculation procedure are described. The comparison of availability performances has been done for an example network. The availability figures are analyzed and proposals for availability design improvement are given.*

Keywords: availability, all-optical network

INTRODUCTION

The paper presents the results of an availability performance analysis which has been carried out within the European project COST 239 - "Ultra-high Capacity Optical Transmission Networks", aim of which is to study feasibility of an European all-optical network (EON), capable of carrying all the international traffic between the European main centers. Different studies of the all-optical network design resulted in two approaches to be evaluated. The main differences of the approaches are in overcoming the problem of both of transmission distance limitation and of topology regularity.

The partitioned network approach provides more optical domains assigned to subnetworks. The core network is highly meshed topology with high percentage of all network traffic. Each peripheral ring sub-network is connected to the core through opto-electronic interfaces (Figure 1). Within the optical domain a re-configurable optical path layer could be established. The topology is optimized according to the cost criteria, fulfilling traffic and fault tolerance requirements, providing the shortest paths between all pairs of nodes.

Optical Network Design and Modelling H. van As & A. Jukan (Eds.)

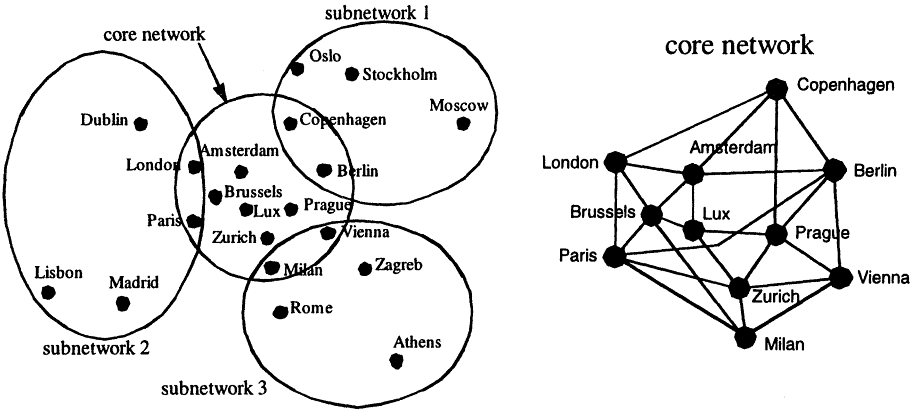

Fig. 1- *Partitioning network - COST 239 case study*

In *the grid connect network* approach a regular topology is used as a virtual one (Figure 2) on the multiplex section layer. In order to maintain the regularity of the network, fulfilling asymetric traffic requirements, "twin-nodes" were introduced (white circles in figure 2). The regularity results in a uniform node structure of low complexity. In this approach the wavelength routing is static. There is no re-configurability in the optical domain (fixed path layer). The optical domain is limited to the predefined depth. In this paper the depth of 2 is assumed comprising for each node an optical domain with 24 surounded neighborous.

In the paper both of approaches have to be compared in terms of availability, analyzing an example sub-network, designed to provide comparable results.

1. ASSUMPTIONS

All the availability measures to be calculated are related to node pair availability (*s-t availability*). Steady-state (asymptotic) availabilities are considered, assuming constant failure and repair rates. The failures in the network are caused by non-self healing outages; every failure has to be repaired. The impact of the node unavailabilities is negligible as compared with the availabilities of optical links. Link failures are assumed to be caused by a failures in the fiber optical amplifiers, or in the fiber cables, causing an interruption of all services in the cable (see the Fig.3). This

assumption is introduced because the data from the field show that the most of failures are caused by "outside interference", dig-ups, craft/workman errors, etc., affecting a high percentage of fibers in the cable.

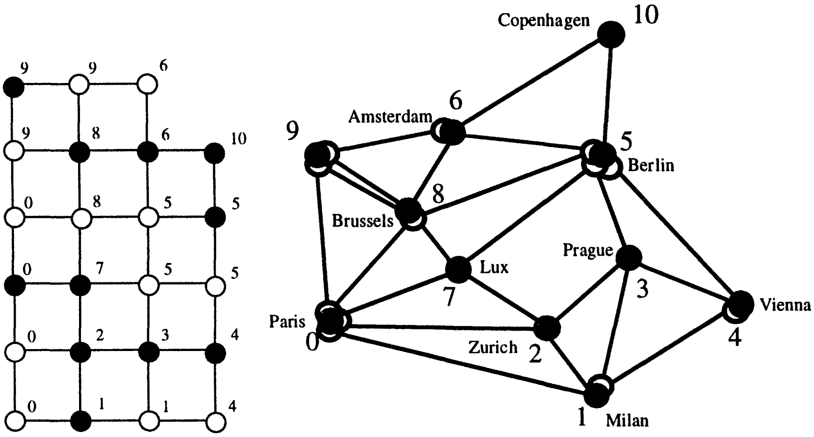

Fig. 2 - *The WDM-Gridconnect - the COST 239 case study*

Availability of one path element is taken to be $A \approx \lambda \cdot MTTR$ where λ is failure rate and *MTTR* is mean time to repair. The values for the λ and *MTTR* are assumed to be: $\lambda_{POA}=\lambda_{BOA}=$ 2000 fit (1fit=number of failures per 10^9 hours), $MTTR_{POA}=MTTR_{BOA}=6$ h, $\lambda_{cable}=114$ fit/km, $\lambda_{OA}=4500$ fit, $MTTR_{cable}=MTTR_{OA}=21$ h. The failures of optical cables and optical amplifiers are mutually independent. The number of optical amplifiers is directly related to the distance between the optical amplifiers. The distance between optical amplifiers is assumed to be 100 km.

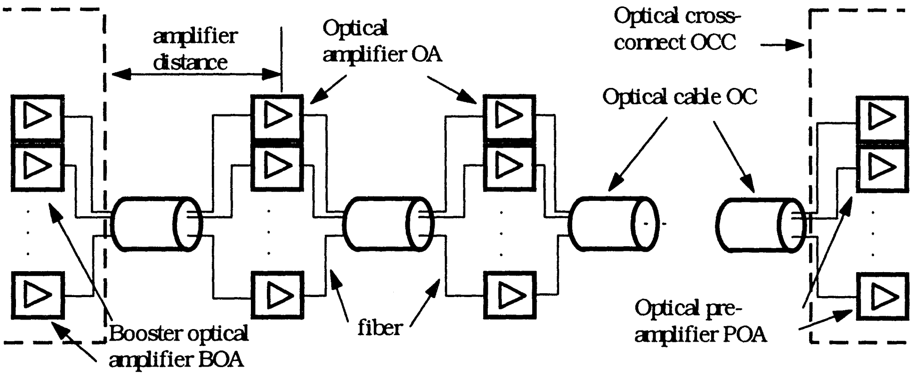

Fig. 3 - *Optical link*

2. AVAILABILITY MODEL

In order to compare the all-optical network approaches from the availability point of view, node pair connection terms were defined and the corresponding availability measures have been adopted. Every term has double meaning: it describes the type of the network connection, and on the other hand, it denotes a logical variable describing the faulty-free condition of the connection, if the variable is in the non-complementary state. The probability of non-complementary state is equal to availability performance. In complementary state logical variable denotes faulty condition. The probability of complementary state is equal to unavailability performance. Which expression will be chosen depends on the expression complexity, given by the number of product terms.

The logical connection LC_{ij} is a bi-directional connection between nodes i and j which fulfills all the traffic or capacity requirements in the directions (i,j) and (j,i). (As a logical variable LC_{ij} denotes a faulty-free condition of logical connection.)

The logical connection between nodes i and j is composed of one or more logical channels.

The logical channel K_{ij} is a bi-directional connection between the nodes i and j which has an indivisible capacity in the optical domain, corresponding in WDM to one wavelength channel at standard bit rates (2.5 Gbit/s, 10 Gbit/s, etc.) for each path.

The relationship between the logical connection LC and the logical channels $K(q)$, $q = 1, 2, \ldots, n$ could be defined, in general, by *the k-out-of-n* principle. Let us consider two cases.

In the case where $k = n$, one can assume that the logical connection contain no spare capacity. In order to fulfill the traffic requirements, all of n logical channels should be in a faulty-free condition, and the successful event of logical connection could be described by Eq. (1´). The complementary form $\overline{LC}(n)$, denoted by (1´´) is given too:

$$LC(n) = \bigcap_{q=1}^{n} K(q), \qquad \overline{LC}(n) = \bigcup_{q=1}^{n} \overline{K}(q) \qquad (1´)(1´´)$$

where $\bigcap$ is logical AND, and $\bigcup$ logical OR operator.

The logical connection availability of type $A[LC(n)]$ and *unavailability* of type $U[\overline{LC}(n)]$ between nodes i and j are defined according to the availability model in Figure 4:

$$A[LC(n)] = \Pr\{LC(n)\} = \Pr\{K(1) \cap K(2) \cap \cdots \cap K(n)\} \qquad (2´)$$

$$U[\overline{LC}(n)] = \Pr\{\overline{LC}(n)\} = \Pr\{\overline{K}(1) \cup \overline{K}(2) \cup \cdots \cup \overline{K}(n)\}. \qquad (2´´)$$

In the case where $k < n$, the assumption is that a logical connection has enough spare capacity, fulfilling traffic requirements with at least k logical channels out of n (total number of channels). This case could happen, if, for example, the electrical SDH level provides a spare capacity for protection purposes. In this case the faulty-(free) condition of logical connection is:

$$LC(k,n) = \bigcup_{p=1}^{M}\left[\bigcap_{r \in Cp}^{k} K(r)\right], \quad \overline{LC}(k,n) = \bigcap_{p=1}^{M}\left[\bigcup_{r \in Cp}^{k} \overline{K}(r)\right], \quad M = \binom{n}{k} \qquad (3´´)(3´)$$

where $K(r)$, ($\overline{K}(r)$) is r-th element (logical channel) out of k, in combination C_p.

The logical connection availability k-out-of-n $A[LC(k,n)]$ between two nodes is defined by:

$$A[LC(k,n)] = \Pr\{LC(k,n)\} \qquad (4)$$

For example, the availability 2-*out-of*-3 $A\left[LC(2,3)\right]$ and the complementary unavailability $U\left[\overline{LC}(2,3)\right]$ for logical connection composed of 3 logical channels, are equal to:

$$A\left[LC(2,3)\right] = \Pr\left\{\left[K(1) \cap K(2)\right] \cup \left[K(1) \cap K(3)\right] \cup \left[K(2) \cap K(3)\right]\right\} \quad (5')$$

$$U\left[\overline{LC}(2,3)\right] = \Pr\left\{\left[\overline{K}(1) \cup \overline{K}(2)\right] \cap \left[\overline{K}(1) \cup \overline{K}(3)\right] \cap \left[\overline{K}(2) \cup \overline{K}(3)\right]\right\} \quad (5'')$$

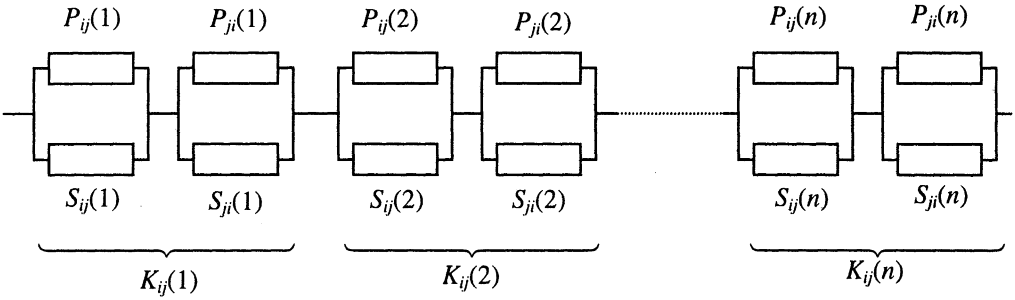

Fig. 4 - *Availability model of logical connection for k = n*

In the topologies under consideration the logical channel is composed of two paths, in redundant structure. In the partitioned network *the primary path* is used in a faulty-free state of the network, and its *spare path* is used if the primary path is faulty. In the grid-connect network both paths, primary and spare, are used in parallel at the same time, as hot stand-by redundancy.

According to the model (Fig.4), the logical channel $K_{ij}(q)$, is faulty-free, if the primary path $P_{ij}(q)$ **or** the spare independent path $S_{ij}(q)$ in one direction **and** the primary path $P_{ji}(q)$ **or** the spare independent path $S_{ji}(q)$ in opposite direction are faulty-free.

$$K_{ij}(q) = \left[P_{ij}(q) \cup S_{ij}(q)\right] \cap \left[P_{ji}(q) \cup S_{ji}(q)\right] =$$
$$= \left[P_{ij}(q) \cap P_{ji}(q)\right] \cup \left[P_{ij}(q) \cap S_{ji}(q)\right] \cup \left[S_{ij}(q) \cap P_{ji}(q)\right] \cup \left[S_{ij}(q) \cap S_{ji}(q)\right] \tag{6'}$$

$$\overline{K}_{ij}(q) = \left[\overline{P}_{ij}(q) \cap \overline{S}_{ij}(q)\right] \cup \left[\overline{P}_{ji}(q) \cap \overline{S}_{ji}(q)\right] \tag{6''}$$

The (un)availability of logical channel $K_{ij}(q)$ is as follows

$$A\left[K_{ij}(q)\right] = \Pr\left\{K_{ij}(q)\right\} \qquad U\left[K_{ij}(q)\right] = \Pr\left\{\overline{K}_{ij}(q)\right\} \tag{7')(7''}$$

The *path* between the two nodes i and j, is a chain of links (i, x), (x, y),..., (z, j) and nodes $(i, x, y,..., z, j)$. Each link the path is passing through, is specified by an optical cable OC_{xy}, and a fiber v in the cable with the corresponding chain of optical amplifiers $OA_{xy}(v)$. Each path is defined in WDM also by a wavelength (or more wavelengths in the case of wavelength conversion), but the wavelength assignment within a fiber has no influence on availability calculation, because all wavelengths are assumed to be equal. Node elements the path is passing through, are multiplexers (WDM), optical switches, etc. The successful event of a *path*, primary P_{ij} or a spare path S_{ij}, could be expressed by (8):

$$path_{ij} = \bigcap (\text{logical variables of path elements}). \tag{8}$$

The faulty-free and faulty conditions of a path q can be expressed by

$$path_{ij}(q) = \left[OC_{ix} \cap OA_{ix}(u)\right] \cap \left[OC_{xy} \cap OA_{xy}(v)\right] \cap \cdots \cap \left[OC_{zj} \cap OA_{zj}(w)\right] \tag{9'}$$

$$\overline{path}_{ij}(q) = \left[\overline{OC}_{ix} \cup \overline{OA}_{ix}(u)\right] \cup \left[\overline{OC}_{xy} \cup \overline{OA}_{xy}(v)\right] \cup \cdots \cup \left[\overline{OC}_{zj} \cup \overline{OA}_{zj}(w)\right] \tag{9''}$$

In the analysis the assumption is that the chain $OA_{xy}(v)$ is faulty-free if all amplifiers in the chain are faulty-free. (In general, any redundant structure of optical amplifiers could be modeled, as well.)

Substituting the sets of simple events, forming expressions (9), into more complex one's, (6), (3), or (2), one can achieve (un)availability expressions for selected (un)availability measures. Table 1 shows the numbers of product terms in union.

The probability calculation to be described in Part 3 must take into account the fact that Boolean products describing different paths in the network could have many elements in common. The grade of dependency of network elements has to influence the availability figures for specific availability calculation cases.

Table 1

	$LC(n)$	$\overline{LC}(n)$	$LC(k,n)$	$\overline{LC}(k,n)$
Number of product terms	4^n	$8nl^2$	$\binom{n}{k}\ 4^k$	$\binom{n}{k}\ 8nl^2$

n - number of logical channels,
k - parameter in *k-out-of-n* structure,
l - average number of links in paths contributing logical channels of one logical connection.

Regarding the unavailability of logical connection $U(LC_{ij})$, a lower U_{LB} and upper bound U_{UB} values for each approach can be determined by using Eq. (2´):

$$U(LC_{ij}) \geq U_{LB} = \max_{m}\left\{U(K_{ij}(q))\right\} \tag{10}$$

$$U(LC_{ij}) \leq U_{UP} \approx \sum_{m=1}^{n} U(K_{ij}(q)) \tag{11}$$

The Eq. 10 shows that a minimum unavailability in *the non-redundant structure of logical channels* (*k=n*) could be achieved if all logical channels of a logical connection are assumed to use for every link in the path, the same optical fiber (with different wavelengths) in one direction. This is the maximum dependency which can be achieved in the partitioned network by using minimum number of path elements. In the grid network, where different path routes exist, in non-redundant case, the unavailability can not be better than the worst channel unavailability.

The upper bound unavailability according to the Eq. 11 reflects the case of maximum independence of channels in each of analyzed approaches. The logical con-

nection makes use of a maximum number of path elements; the channels are assigned to different optical fibers within the same cable in the partitioned network, or they are assigned to different cables in the grid network.

3. AVAILABILITY CALCULATION

The availability calculation to be done is based on development, minimization and transformation of a Boolean product union, until a sum of disjoint union of products is achieved, assuming each product is composed of independent events. After finishing this procedure the (un)availability performance can be calculated as a sum of Boolean product probabilities.

The (un)availability measure of the logical connection, being the most complex one, is calculated through the following steps:

1. Formation of a logical expression of the logical connection faulty-(free) condition, comprising expressions of logical channels, paths and path elements (OCs and OAs).

2. Transformation of a logical expression into the union of (non-disjoint) terms by performing AND (OR) operation on expressions (6) for the logical channel itself and adding step-by-step new terms defined by the expressions (2) or (3).

In order to reduce the exponential growth of the term number in the union, the minimization could be applied after each multiplication, according to the following rules:

$ab \cap ac = abc, \quad a \cup ab = a$ where a, b, c could be any Boolean product.

3. Obtaining a disjoint union of products using the algorithm of Abraham [4].

4. Alternating the calculation of partial availability A_p and partial unavailability U_p, as sums of term probabilities. A satisfactory result is achieved if A_p - U_p < *prescribed error.*

4. EXAMPLE SUBNETWORK

In order to compare two network approaches from the availability point of view two nodes are selected (Milan, Berlin) forming an example sub-network (Figure 5) with specified logical channels, paths and fibers in both approaches. Both logical connections contain 4 logical channels within optical domain.

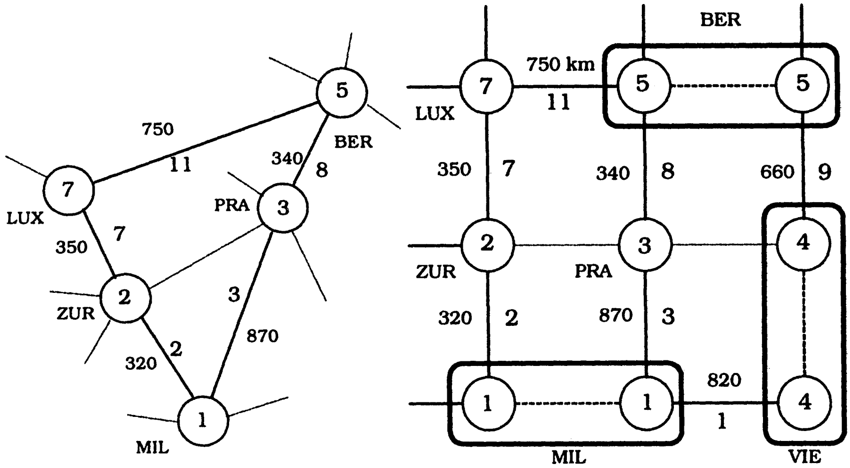

Fig. 5 - *An example sub-network*

In the partitioned network the paths (primary and spare) are chosen as the first and the second shortest paths, respectively. All logical channels have the same path routes. The option in the partitioned network could be the usage of fibers in optical cables. Two extreme cases will be analyzed. In the first case (P1) all paths, assigned to the same route, use only a single fiber within one optical cable, but different wavelengths. In the second case (P4) each path of all logical channels uses a separate fiber in the same optical cable. In this case for every direction 4+4 fibers are used.

In the grid network (G) the paths and the related logical channels are chosen according to prescribed rules of regular topology. As a consequence assignment options are not possible. Different logical channels could have different path routes. At least one of logical channels in the grid network has the paths with the same routes as the logical channels in the partitioned network. The analysis should point out how this "lack of freedom" in regular network could influence on the availability performance.

The routes for the above three cases are shown in Figure 6. The logical connection is described as follows:

source_node - termination_node (number_of_logical_channels) { logical_channels }

For each logical channel both directions, (> and <) could be defined, and for each direction a primary and a spare path are specified:

number_of_logical_channel > primary_path | spare_path]
< primary_path | spare_path];

The paths are described as a list of optical links *Lx(f, w)* where *Lx* denotes link *x*, and *f* and *w* are the assigned fiber and wavelength, respectively.

```
Partitioned network - 1 fiber - case P1
Mil - Ber ( 4 ) {
i     > L3(1,i) - L8(1,i) | L2(1,i) - L7(1,i) - L11(1,i) ]
      < L8(2,i) - L3(2,i) | L11(2,i) - L7(2,i) - L2(2,i) ];

For logical channel K(i), i= 1, 2,...,4
the wavelengths are λi=i
}

Partitioned network - 4 fibers -case P4
Mil - Ber ( 4 ) {
1     > L3(i,1) - L8(i,1) | L2(i,1) - L7(i,1) - L11(i,1) ]
      < L8(i+4,1) - L3(i+4,1) | L11(i+4,1) - L7(i+4,1) -
      L2(i+4,1) ];

For logical channel K(i), i= 1, 2,...,4,
the fibers are i for > direction and i+4 for < direction
}

Grid network - case G
Mil - Ber ( 4 ) {
1     > L1(1,5) - L9(3,5) | L3(8,5) - L8(9,5) ]
      < L8(5,2) - L3(6,2) | L9(12,2) - L1(11,2) ];
2     > L1(3,1) - L9(3,1) | L2(8,1) - L7(9,1) - L11(8,1) ]
      < L11(6,1) - L7(5,1) - L2(6,1) | L9(12,1) - L1(12,1) ];
3     > L3(2,4) - L8(3,4) | L2(8,4) - L7(9,4) - L11(7,4) ]
      < L8(5,3) - L3(6,3) | L9(12,3) - L1(11,3) ];
4     > L3(2,5) - L8(3,5) | L2(8,5) - L7(9,5) - L11(7,5) ]
      < L11(4,2) - L7(5,2) - L2(6,2) | L8(12,2) - L3(13,2) ];
}
```

Fig. 6 - *Logical connection - logical channel - path - link - fiber - wavelength assignment*

5. AVAILABILITY FIGURES

The results of the availability calculation for three cases, in the non-redundant and redundant structures of logical channels forming a logical connection, are shown in Table 2.

Table 2 - *Availability of logical connection (LC_{15}) Milan – Berlin*

		Partitioned network		Grid network Case *G*
		Case *P*1 (1 fiber)	Case *P*4 (4 fibers)	
No.	**non-redundant structure of logical channels**			
1	Unavailability of logical connection *U(LC)* **x10^{-5}**	2.74914	8.02586	8.99495
	No. of logical channels (both directions)	4+4	4+4	4+4
	No. of fiber per *LC*	2	8	12
	Unavailability of logical channels $U(K(q))$ **x10^{-5}**			
2	$q = 1$	2.74914	2.74914	3.81166
3	2			4.16115
4	3			2.74914
5	4			2.74914
6	U_{LB} - lower bound of *U(LC)*, $\max_i\{U(K(q))\}$	2.74914	2.74914	4.16115
7	U_{UP} - upper bound of *U(LC)*, $\sum U(K(q))$	10.9966	10.9966	13.4711
	redundant structure of logical channels			
	Unavailability of the logical connection *k-out-of-n* $U(LC(k, n))$ **x10^{-5}**			
8	$U(LC(1, 4))$	2.74914	0.98318	0.00611
9	$U(LC(2, 4))$	2.74914	0.98314	1.87571
10	$U(LC(3, 4))$	2.74914	1.00438	3.81765

The comparison of the unavailabilities of the logical connection (No.1: *P*1 c. *P*4) (c. stands for *compared to*) for non-redundant structure shows the influence of the dependency by using a single or more fibers in the same cable.

The comparison (No.1: *P* c. *G*) gives for cases *P*1 and *P*2 better (lower) unavailabilities, because logical channels in grid network use more than one path route.

All logical channels (No.2 - 5: *P*) have the same values of unavailabilities. This is due to the fact that all channels use the same path routes (the same optical cables and equal number of optical amplifiers). The unavailabilities (No.2 - 5: *G*) differ because these channels use different path routes (lengths) which are not "shortest paths optimized". The more elements are used in the non-redundant structure, the higher unavailability values are achieved.

The different bound values (No.6-7: *P* c. *G*) reflect the way of path-fiber-wavelength assignment in the different approaches.

Comparing figures for redundant structure, the grid network shows better figures for high redundancy (No.8: *G* c. *P*) and (No.9: *G* c. *P*1). The more elements are used in redundant structure, the lower unavailability values are achieved.

CONCLUSIONS

In the paper the availability performances and availability model of an all-optical network are defined, and the availability calculation procedure described. The implemented tools are used to calculate and compare availability figures of two network approaches. The point was not to achieve the absolute availability figures for the selected approaches, because the availability data for the future all-optical network can not be estimated precisely enough. The comparison results intent to point out some suggestions for availability design improvement.

In the case where a non-redundant structure of logical connection is used, or for dimensioning of logical channels in any case, one should prefer the solutions where is as less number of network elements as possible. For example, a failure of an optical amplifier affects less number of logical connections, if more logical channels of one logical connection use the same fiber (the same chain of optical amplifiers). Those solutions should be preferred too, which use the same cable for logical channel path routes in both directions. The same conclusion could be stated for the usage of cross-connect elements in a node, the logical channels are passing through. Note that every design should maintain the independence of the primary and the spare paths.

If a redundant structure of the logical connection is used, one should evaluate for particular design which one of two opposite influences could overrule: the influence of the unavailabilities of equivalent logical channels, "shortest path minimized", or the influence of the unavailabilities of redundant structure comprising logical channels with different path routes, where all paths can not be the shortest one's.

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Performance Analysis of a combined WDM/TDM Network based on fixed Wavelength Assignment

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Abstract

Photonic telecommunication networks gain increasing importance in various fields extending from access to wide area networks. Due to limitations of fast all-optical switching technology, many promising concepts are based on circuit switching. In this paper, we propose a new and simple star topology using *fixed* wavelength assignment and a combination of wavelength and time division multiplexing. Owing to the fixed assignment, no tunable components or wavelength converters are needed in the central star element. For this system architecture, we present a performance evaluation based on a probabilistic method to calculate call blocking probabilities, which is validated by simulation and compared to a rough approximation based on a simple loss system. The results allow to evaluate the trade-off between capacity increase either by additional wavelengths or additional time slots in the system.

Keywords

Optical Star Network, WDM, TDM, Performance Analysis

1 INTRODUCTION

Photonic networks attract raising attention due to several advantages of optical technology like huge transmission capacity of optical fibers and increasing network reliability due to optical transmission. An important aspect is wavelength division multiplexing (WDM), which allows the transportation

Optical Network Design and Modelling H. van As & A. Jukan (Eds.)

of multiple wavelengths on one fiber without interference. Additionally, this mode profits from EDFAs (Erbium Doped Fiber Amplifiers) which allow the simultaneous amplification of multiple wavelengths.

The increasing interest in photonic networks is manifested by several special issues published lately [10, 11]. They show that the focus is moving from component oriented research towards network aspects and display the wide scope of applications ranging from on-chip communication to wide area networks (WANs).

The great progress made in the last few years can be seen by a comparison with the state of the art at the beginning of this decade [4]. Numerous network concepts, which can be classified in single-hop and multi-hop systems [17, 18], have been proposed since then. A large part of the proposals considered star based networks which are supposed to be mainly applied as local or metropolitan area networks (LANs, MANs) with higher transmission rates than today [24]. But there were also suggestions to build wide area telecommunication networks using star networks (for example in [8]).

Up to now, most concepts were based on packet transmission mode. Nevertheless, recently circuit switching again attracted more attention [9], since it is possible to show that for some application areas circuit switching offers serious advantages over packet switching [22].

In this work, we will therefore concentrate on the call level in a circuit switched WDM star network. However, instead of a broadcast star coupler as central element, we propose a simple exchange element using fixed wavelength assignment. The network could be favorably applied as a regional network where single end users are connected with moderate bit rates (i.e. a fraction of a wavelength's bandwidth). Most likely, pure WDM systems will play a minor role to connect end users because the bandwidth available on a wavelength cannot be fully utilized by a single user. Moreover, the enhancement with TDM offers a simple way to allow multiple connections for each user. Thus, we will concentrate on combined WDM/TDM systems in this work.

The following section describes the proposed architecture. Section 3 gives an overview on possible performance evaluation methods whereas Section 4 contains the modeling and analysis. After presenting some results we conclude with an outlook on further work.

2 NETWORK ARCHITECTURE

For the physical topology a star structure is supposed. However, instead of using a passive star coupler, we apply fixed wavelength routing in the star, which can be realized with simple grating elements [16]. Thus, the wavelength that has to be chosen for a transmission is explicitly determined by the link to which the destination node is connected. Figure 1 shows a simple example with 3 links connected to the star. m end stations (each comprising one transmitter

and one sender) are connected to every link. They have common access to a time slots carried on each wavelength of a single link.

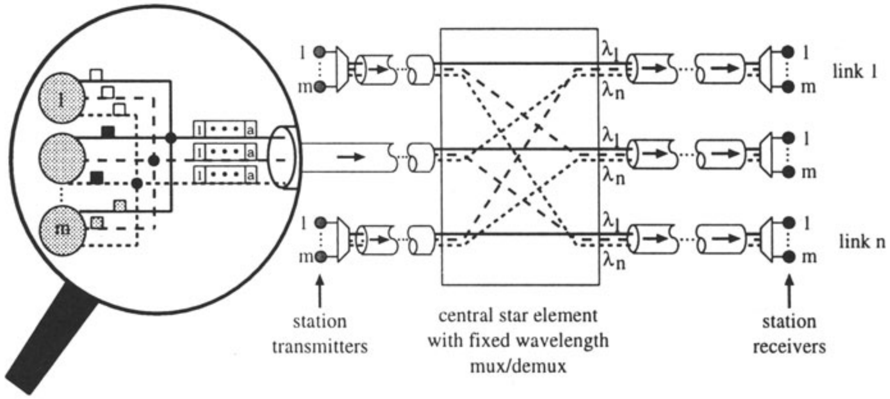

Figure 1 Network architecture

This architecture provides several advantages concerning technological demands and implementation complexity.

- No tunable elements are required in the star exchange element leading to reduced realization cost.
- Fixed wavelength routing offers various advantages. It can be realized using simple and fixed elements. In [8], the principle of a simple grating device is shown allowing wavelength multiplexing and demultiplexing. Progress for integrated wavelength demultiplexers based on waveguide arrays was announced recently for example in [19] and [21]. Moreover, there is no signal splitting amongst multiple links and therefore the power degradation is less than in the case of passive broadcast star couplers. Furthermore, the limited set of available wavelengths can be reused in the proposed fixed arrangement allowing a multiple, simultaneous use of the same wavelength on different links.
- No wavelength converters are required. These elements are still complex and difficult to realize (see for example [25]). In particular to achieve satisfying all-optical solutions, a lot of research is still necessary.
- In our system, we carry multiple time slots of constant length on each wavelength. When a connection is established, the wavelength access is periodically assigned to the stations for a certain period of time. During this time, a transparent channel that is independent of signal format or bit rate is available for the stations. The length of a slot depends on the achievable tuning speed of optical components on the one hand and the maximum allowed packetization delay on the other hand.

From a technological point of view, several promising results were reported for OTDM (Optical Time Division Multiplexing). A practical use seems realistic in the near future and various groups are working on a quick introduction of OTDM networks [2]. An up to date overview and description of the state of the art is given in [20].

For the described architecture, one wavelength is required for each link connected to the star (i.e. as many wavelengths have to be transported in WDM mode as links are connected). The architecture could be extended by using multiple fibers for each link. Nevertheless, this requires more resources (i.e. transmitter and receiver) at the stations. Moreover, bidirectional transmission on a wavelength by using directed couplers could be used instead of using one fiber for each direction as shown in Figure 1.

To achieve a real system, some extensions would be necessary like for example the implementation of a network control and management instance as well as signaling facilities.

In combined WDM/TDM systems it is of high interest to work out the relations between the parameters like number of WDM channels, bit rate per channel, and number of fibers. Recently, some work was reported to evaluate the trade-off between these parameters from an economical and technological point of view [7, 15]. Another interesting perspective is a comparison with regard to traffic theoretical aspects. In the following, we present a method which allows a comparison of call blocking probabilities.

3 PERFORMANCE EVALUATION METHODS

A number of performance evaluation methods for WDM based star networks are reported in literature. In [14], Lu and Kleinrock consider a packet transmission star network with uniform and non-uniform traffic as loss system, i.e. blocked packets are discarded. A mathematical model is derived based on birth-death processes which lead to Markov chains for resource occupancies (i.e. wavelength, transmitter, and receiver occupancies).

For circuit-switched WDM/TDM networks, many results can be adapted from earlier work on "classical" electrical networks. In [12] an approximation is introduced while [5] presents a decomposition method that allows the exact calculation for call blocking probabilities in circuit-switched networks. The latter method does not depend on the routing matrix and focuses on computational savings for large arbitrarily meshed network structures.

Other work is concerned with call blocking probabilities in circuit-switched integrated services networks. In [6], a loss system is considered with a variable number of channels per call. However, the method assumes fixed routing and has to make several approximations for larger networks.

Recently, Awater et al. presented an exact computation of time and call blocking probabilities in multi-traffic, multi-resource loss systems with com-

pletely shared resources and gave also an overview of related work [1]. The proposed algorithms were stated to be stable and to achieve an efficiency comparable to earlier proposed approximations.

For performance investigations of systems like the one described in Section 2, there are several suitable methods:

- Analyzing the state space of a system leads to exact results for pure chance traffic. However, it is necessary that each state of the system and all transition rates between any two states are considered. Therefore, this method results in large systems of linear equations practically unsolvable for networks with realistic complexity. Numerous approximations were deployed in the past to reduce computing requirements.
- Another group of approximations comprises transformations to well known link systems as spatial equivalents. In this field, numerous methods for investigations of multi stage system as for example iterative improvement of supposed link occupancy distributions are reported in literature (see the detailed overview in [13]). But up to our knowledge, there is no method directly adaptable to our problem.
- Probabilistic methods combined with permutation investigations can also lead to exact results. Due to the high complexity of real systems however, simplifying assumptions as for example simple traffic characteristics and statistical independence of states are often necessary.
- In principle, simulative investigations allow an examination of any system. However, there exists also a trade-off between accuracy and computing effort. Nevertheless, simulations are a valuable tool in confirming analytical results. Moreover, they allow extensions to traffic types or protocols which are not analytically tractable.

In the following, we present a probabilistic method to investigate our system. The analytical results are verified by simulation.

4 MODELING AND ANALYSIS

Table 1 lists the parameters used for the following analysis.

n	number of links (equals number of wavelengths)
m	number of stations per link
a	number of time slots per wavelength
λ	rate of connection requests from each station
ε	reciprocal mean holding time of a connection

Table 1 System parameters for analysis

Each connection between two end users occupies one time slot. A source selects a receiver randomly out of the $n \cdot m$ stations connected to the network*. The optical wavelength which the new connection will be carried on is determined by the *fixed wavelength routing* scheme introduced before. Let S be the random variable denoting the number of time slots occupied at the source transmitter just before the new connection is to be set up. Let J be the random variable for the occupation of the sending channel, i.e. the number of time slots occupied on the wavelength which must be used to route the connection to the selected receiver. Finally, let D be the random variable for the number of time slots occupied at the destination station's receiver.

Assuming stationarity, we have the following Erlang probability distributions for loss systems for S, J and D. Here, the loss due to blocking at other places is neglected.

$$\mathrm{P}\{S = s\} = \frac{\frac{A_S^s}{s!}}{\sum_{i=0}^{a} \frac{A_S^i}{i!}} \quad \text{for } 0 \leq s \leq a \tag{1}$$

$$\mathrm{P}\{D = d\} = \frac{\frac{A_S^d}{d!}}{\sum_{i=0}^{a} \frac{A_S^i}{i!}} \quad \text{for } 0 \leq d \leq a \tag{2}$$

$$\mathrm{P}\{J = j\} = \frac{\frac{A_W^j}{j!}}{\sum_{i=0}^{a} \frac{A_W^i}{i!}} \quad \text{for } 0 \leq j \leq a \tag{3}$$

In equations (1) and (2), the offered traffic per station A_S is given by

$$A_S = \frac{\lambda}{\varepsilon} \tag{4}$$

and in equation (3) the offered traffic per wavelength A_W is given by

$$A_W = \frac{m}{n} \cdot A_S \tag{5}$$

Assuming independence** of S and J and random selection of one out of the free time slots at connection set-up, we find the distribution for the number of

*The case of a source connecting to itself is not excluded from the following analysis because it would make the analysis much more complex without significantly changing the results.
**This assumption is quite accurate owing to the fact that m users have access to each wavelength and the connections of a single user are uniformly distributed over all n wavelengths on a link.

time slots Q which are free at the source transmitter *and* on the wavelength:

$$\mathrm{P}\{Q = q|S = s, J = j\} = \frac{\binom{a-s}{q}\binom{s}{a-j-q}}{\binom{a}{a-j}} \quad \text{for } q \in [\max\{0, a-j-s\}, \min\{a-j, a-s\}] \tag{6}$$

Now, proceeding to the destination receiver, we are looking for the probability of loss under the condition that we can choose from Q time slots on the wavelength and there are D busy time slots at the receiver. Loss occurs if all Q time slots are busy at the receiver:

$$\mathrm{P}\{\mathrm{loss}|Q = q, D = d\} = \frac{\binom{d}{q}}{\binom{a}{q}} \quad \text{for } q \leq d \tag{7}$$

Defining the binomial coefficient $\binom{a}{b}$ to be zero for $a < b$, $a < 0$ or $b < 0$ and taking S, J and D to be independent, we obtain the loss probability from (6) and (7):

$$\begin{aligned} B &= \sum_{s=0}^{a}\sum_{j=0}^{a}\sum_{d=0}^{a}\sum_{q=0}^{a} \mathrm{P}\{\mathrm{loss}|Q = q, D = d\} \cdot \mathrm{P}\{Q = q|S = s, J = j\} \\ &\quad \cdot \mathrm{P}\{S = s\}\mathrm{P}\{J = j\}\mathrm{P}\{D = d\} \\ &= \sum_{s=0}^{a}\sum_{j=0}^{a}\sum_{d=0}^{a}\sum_{q=0}^{a} \mathrm{P}\{S = s\}\mathrm{P}\{J = j\}\mathrm{P}\{D = d\}\frac{\binom{a-s}{q}\binom{s}{a-j-q}}{\binom{a}{a-j}}\frac{\binom{d}{q}}{\binom{a}{q}} \end{aligned} \tag{8}$$

5 RESULTS

Comparison for systems with a given number of stations

Using the parameters of our system according to table 1, we get the total number of stations in the system m_{total}:

$$m_{total} = n \cdot m \tag{9}$$

Moreover, the number of resources (i.e. slots) per link is given by

$$R_{link} = n \cdot a \tag{10}$$

and the number of resources in the star element by

$$R_{star} = n^2 \cdot a \tag{11}$$

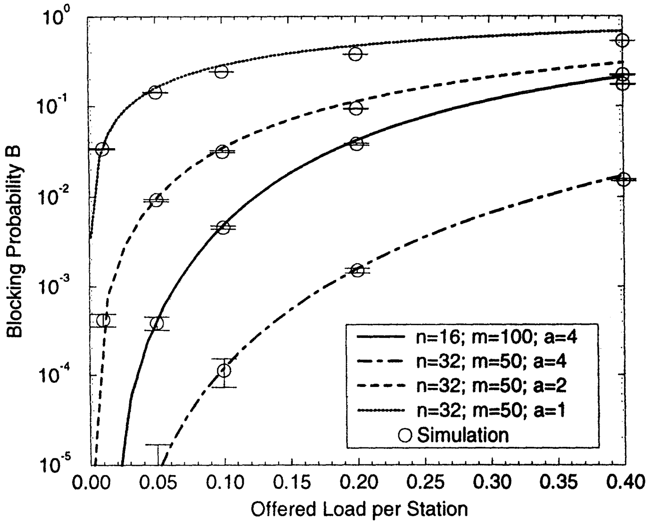

Figure 2 Call blocking probability for $m_{total} = m \cdot n = 1600$ stations

Figure 2 shows the call blocking probability versus the offered load per station A_S for a system with $m_{total} = 1600$ stations. The solid line represents a system where $m = 100$ stations are connected to each of the $n = 16$ links* and $a = 4$ time slots are available on each of the 16 required wavelengths (we name this system *reference system* in the following).

The dashed lines describe also a network with $m_{total} = 1600$ stations, but now using $n = 32$ links with $m = 50$ stations per link. It can be seen that for the same value of $a = 4$ the blocking probability decreases significantly due to the reduced traffic per wavelength. Compared to the reference system, $a = 2$ leads to higher blocking probabilities although R_{link} is constant and R_{star} is even doubled. This is due to the smaller bundles resulting in a smaller economy of scale. For the case $a = 1$, leading to the same R_{star} as in the reference system, blocking probabilities are even higher.

Figure 2 also contains simulation results which are depicted with a 0.95 confidence interval in all figures. They indicate that the analytical results are overestimating the exact values for high loads. This effect is due to the influence of the correlation between the link, transmitter and receiver states which we neglected in our analysis. This correlation slightly decreases the blocking probabilities at high traffic load per station.

*At present, a number of channels in a WDM system in the range of 8 to 32 is under discussion at standardization bodies.

System Scalability

Figure 3 shows the influence of system scaling on blocking probabilities. Compared to our reference system, increasing m to $m = 200$ and therefore doubling m_{total} leads to higher blocking probabilities as expected. However, if we simultaneously double the number of time slots a to $a = 8$ thus holding R_{link}/m constant, we see lower blocking probabilities. This can be explained by the economy of scale.

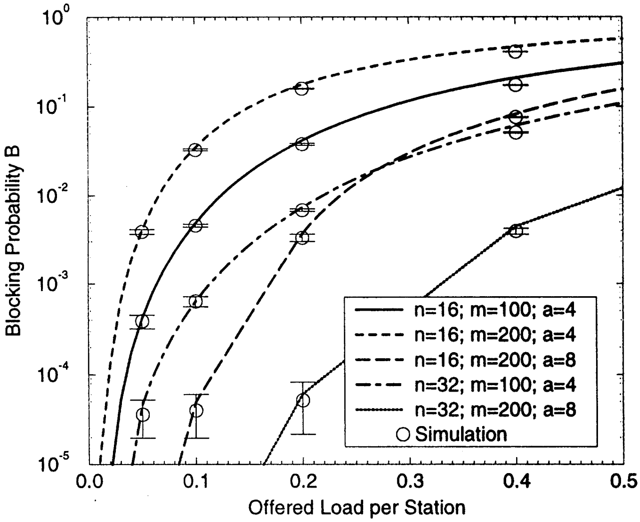

Figure 3 Blocking probability for scaled systems

Another way of doubling the system size is doubling the number of attached links ($n = 32$). If m and a are not changed, we see a reduction of blocking probabilities although m_{total} is doubled. This can be explained by the increase of resources according to (10) and (11). As R_{link} grows proportional to n, the number of resources available for a bundle of m stations is doubled. Moreover, R_{star} grows quadratically with n.

This is also the reason that the results for twice as many stations per link ($n = 32$, $m = 200$, $a = 4$) are *identical* to the reference system although now m_{total} equals 6400. Obviously, blocking probabilities decrease further if we additionally raise a to $a = 8$.

For high traffic load per station, we see again slightly higher blocking in the analytical results compared to simulation, as discussed before.

It can be seen that system scaling based on additional links improves the performance while the number of time slots per wavelength (and thus the re-

quired tuning speed for each station) remains the same. However, the effect of decreasing blocking probabilities with increasing number of stations is limited by the number of wavelengths which have to be transported in WDM mode. Moreover, the stations are more complex if they have to support a higher number of wavelengths.

Approximation

Finally, we present a simple approximation for our system based on a $M/M/a$ loss system. Here, we neglect sender and receiver blocking and approximate our system with a loss system for each wavelength on a link. The number of servers equals a (i.e. the number of time slots on a wavelength) and the offered load is A_W as given by equation (5).

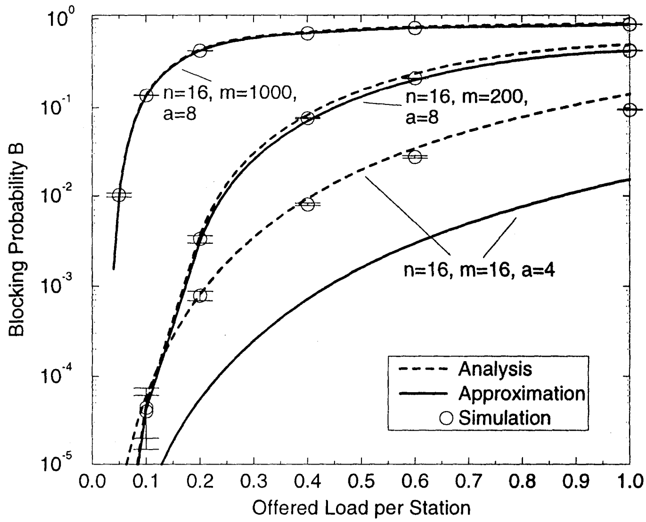

Figure 4 Comparison of exact and approximate solution

Figure 4 shows the blocking probabilities calculated according to (8) (dashed lines) and the results of the approximation (solid lines) versus the offered load per station A_S. It can be seen that for $m >> n$ the approximation is very accurate. However, with decreasing the ratio m/n, the approximated blocking probabilities are too low because sender and receiver collisions are neglected. Moreover, the simulation corresponds with the exact analysis for a wide range of A_S. The approximate results can be improved by additionally considering sender and receiver collisions with simple loss systems. Nevertheless, this leads

only to a small improvement and the results remain below the simulated values. Thus, formula (8) is especially useful for m/n not too large.

6 CONCLUSION

In this paper, we proposed a new WDM/TDM network architecture based on a simple star exchange using fixed wavelength assignment. For this architecture, we presented a performance evaluation based on a probabilistic method to calculate call blocking probabilities for circuit switching mode. Moreover, we depicted a simple approximation which leads to quite accurate results for specific parameter choices. The analytical results allow the evaluation of the trade-off between wavelength and time slot resources in the network.

The proposed model can be extended in several ways. An interesting field already well known in classical networks [3] is the influence of hunting modes for the available time slots. Instead of implementing a random selection of free time slots, the performance could be increased by other searching modes like for example *first free first.* Moreover, time slot interchanging or wavelength routing in the star element or even time slot rearrangement for existing connections [23] could be considered. However, these extensions will lead to increasing system complexity as well as analytical complexity.

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